BETWEEN 3-D COMPUTER MODELS AND 3-D PHYSICAL MODELS: PEOPLE'S UNDERSTANDING AND PREFERENCE

A Dissertation

by

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ABSTRACT

Good communication between architects and clients is an important factor for a successful architectural project. It is critical for architects to present their design ideas effectively and unambiguously to reduce or eliminate their clients' misunderstanding. For people who are not professionally trained in architecture, a three-dimensional (3-D) model is one of the most effective medium of communication. The purpose of this study is to compare laypeople's understanding and preference of digital and physical models, how these models are used in design practice and how architects evaluate their client's understanding and preference. In such context, this research study consisted of a quantitative phase and a qualitative phase. The quantitative part of the study compared desktop-Based interactive 3-D architectural models to physical models by investigating laypeople's understanding of spatial layout and their preferences regarding these two models. An office complex and a single-family residence building were designed, and each type was represented by both physical and digital forms with the same level of detail. Participants were asked to memorize the building components and reassemble them Based on their memory. The qualitative phase involved a series of semi-structured interviews with eight experienced design professionals, its aim was to collect their opinions about how they perceive their clients' preferences and understandings of these two types of models during their practice. The data from both phases were analyzed. In general, Results from the quantitative phase reveals that laypeople who studied physical models performed their tasks significantly better than those studied digital models. The qualitative phase discusses architects' choice of models, the factors that drive their

decisions, the communication with clients, and their clients' understanding of those models.

DEDICATION

To my beloved wife, Zhouzhou Su

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CHAPTER I

INTRODUCTION

1.1 Background

Individuals have been making models for thousands of years. The Egyptian and Greco-Roman peoples created architectural models as symbols, and structural models, such as arches, were made by masons in the Middle Ages (Mills, 2005).

In architectural design practice, the use of "presentation" or "client" models has a long history. Such models are commonly used by architects to convey ideas to their clients and public, to attract the support of patrons, and to thoroughly understand the implications of the designer's plan and section drawings. An example from history is the design competition of the Santa Maria del Fiore during the 14th century, when several presentation models of the great dome were constructed (King, 2000; Mills, 2005). Architectural models started to become quite sophisticated in the early twentieth century and continue to flourish in the contemporary era (Moon, 2005).

In today's architectural design practice, three-dimensional (3-D) models are used intensively during the Schematic Design (SD) phase. As the American Institute of Architects best practice guidelines note, architects develop "study drawings, documents, or other media that illustrate the concepts of the design and include spatial relationships, scale and form for the owner to review" (Lough, 2011, BP 14.02.02). The deliverables during the SD stage often include computer images, renderings or models. As the first stage of a design project, the SD phase helps the client to understand the designers' intent, to resolve major issues related to planning and site design, and to comprehend spatial and volumetric relationships. Thus, deliverables in this phase represent important information.

1.2 Problem Statement

Today, architectural design practice is benefitting from the boom in technology and variety of design media. The increasing popularity of BIM (Building Information Modeling) and other new technologies are creating a paradigm shift in the way designers approach their problems. Previously, computers were mainly used for drafting purposes, but they are now incorporated into every niche of the design process, including conceptual design, rendering and presentation. Thus one question arises: is it reasonable to allow computers to handle EVERYTHING in the design process?

Undoubtedly, the role of computers is superior to the role of analogue techniques in many areas. Computer programs allow designers to make changes easily and they enable expanded integration between architects, engineers and contractors, especially in the era of Building Information Modeling. But in certain areas, especially regarding design representation, debates still exist - do traditional tools still perform better than computers? Alternatively, have digital tools caught up with traditional tools in every aspect?

1.3 Representation Media in the Context of Architectural Practice

1.3.1 The Need for Research

Design communication is a core components in the design process, and the medium has a significant impact on the effectiveness of communication. Apart from the nature and clarity of the information provided, the tools themselves have implications.

Marshall McLuhan in *Understanding Media: The Extensions of Man* (1964) argued that the medium is the message and it impacts the nature of human culture.

Researchers have been investigating different types of design media for a long time and new technology is being developed continuously and studied intensively. According to the architects I interviewed, the media they most commonly use are physical and desktop digital models. A literature review of those media is presented in the following chapter. Those models are believed to bear significant value for the communication between architects and their clients, thus a better understanding of their effects, and how well they assist clients in evaluating the design projects is needed.

Furthermore, despite the richness of information about media and their attributes, only a small number of research studies have directed their attention toward the context of architectural practice. Given the complexity, dynamics and social milieu of the industry, the use of media has become a multi-faceted problem and a more comprehensive methodology should be sought.

1.3.2 The Outline of Research

This study was carried out in the context of architectural practice, with the emphasis on investigating the communication between architects and clients.

Often, researchers have chosen a quantitative approach to understand the characteristics and effects of media, since many variables used in their studies have been developed and quantified over the years, such as distance estimation (Caird & Hancock, 1992). Likewise, the first part of this study adopts a quantitative approach. A set of testing instruments was designed in both physical and digital forms, which were then used to conduct a series of experiments. This part investigates people's ability to understand different types of media.

However, merely to find out whether one media surpasses another in certain areas does not hold practical value for day to day architectural practice. To draw a better overall picture of this topic, the second part of the study introduces a qualitative methodology. The data was gathered by interviewing a number of licensed architects with rich experience in the design industry. Creswell (2009) claimed that studies may benefit from using mixed methods to get a more holistic view of the subject matter. I believe that the use of mixed methods has helped me reach a deeper understanding of the use and implications of media, as well as how they are evaluated by architects and clients.

It should be noted that in this dissertation, the qualitative phase is brought forward and reported before the quantitative phase, since the data from interviews can better complement the research background and literature review. Generally, architects who participated in the interviews provided a broad spectrum of information and a more comprehensive outlook to the subject of inquiry.

In summary, by using a combination of research methodologies I answer some of the questions regarding the effects of presentation media, and their practical applications. More importantly, I provide insights for architects for interacting with their clients in the future.

1.4 Research Questions

Since 3-D computer models and physical models are two of the most widely used media in architectural design communication, comparison studies between these two models is important for better understanding the communication between designers, clients and the general public. A study of spatial layout and model preferences was designed to examine the reactions of non-designers when they viewed the two model types.

1.4.1 Quantitative Questions

The quantitative part of this study addresses the following questions:

- Do laypeople show different levels of understanding between physical models and digital models in terms of spatial layouts?

Researchers consider the understanding of spatial layouts as a factor to evaluate people's understanding of a 3-dimensional space and a gaming task testing people's memory of spatial layout can be a valid measurement for understanding. (Schnabel & Kvan, 2003). The answer to this question may provide insights for architects and increase their efficiency in client meetings throughout the design process.

- Do laypeople show different levels of preference between physical models and digital models?

Like the first question, this is a prolonged debate, even amongst professional architects. Some driving forces for the choice of media are experiences, preference, time, cost, and in many occasions, the curiosity and crave for newer and trendier technology. This study investigates this question from a quantitative standpoint through the use of controlled experiments. In this research context which the participants were asked to compare different scenes, the measurement of preference can be achieved by the ratings of pleasantness, as discussed and used in the research studies by Stamps (1993a, 1993b, 1994).

- Does different types of architecture affect a laypeople's understanding and preference?

Different types of architecture must be tested to cover a broader range of situations. The level of understanding may differ if the layout changes.

1.4.2 Qualitative Questions

The qualitative part of the study aims to answer the following questions:

- What are the commonly used media in use today?

Architects from the front line of practice will provide the most reliable information of the status quo of the industry, including the media they choose during client meetings.

- What are the advantages and disadvantages of the media architects choose?

Real world scenarios may differ from what we have seen in lab results, which contributes to the dynamics of the practice.

- How do design professionals perceive their clients' understanding of and preference for physical and digital models?

Interviews focusing on architects' interactions with their clients were conducted. This information complements the quantitative data, adding an understanding of its validity and possible revelations in real world scenarios.

- What is the reasoning behind architects' choices of models?

It is important to understand how architects keep their clients "in the loop," as well as the merits and caveats of the methods they choose. This information, when synthesized with the quantitative findings, may reveal better solutions for architects and the practice in general.

CHAPTER II

LITERATURE REVIEW

2.1 The Culture of Practice and Design Communication

A common trait amongst architectural professionals is the emphasis on individualism and the intrinsic value of their creativity. In an AIA survey, "design quality" ranked as the number one issue for architects, even more important than adequate compensation (as cited in Cuff, 1991). However, being a service industry dependent upon patronage, commissions come at the price of restrictions, disagreements and accountability. The social milieu of architectural practice is considered to be a significant part of the culture, which is characterized by the relationship between architect and client. Contemporary architectural clients are actively involved throughout the design process, giving constraints, advice and approval. This relationship relies on a delicate balance, as described by Cuff:

> Professionals attempt to maintain a 'service ideal' wherein the profession's function and the intrinsic value of the work are advanced. At the same time the profession remains more or less independent from those it serves. This is a delicate balance, since too much autonomy can eliminate the market for services, while too much service may reduce the architect's power (p. 35).

Pleasing clients has become the main emphasis for many architects in order to maintain a steady profitability in the long run (Siva & London, 2011). The downside of the client-oriented model, however, is a compromise of the underlying architectural values and culture (Gutman, 1988). On the other hand, if too much of the architectural practice is peer-oriented, clients may feel isolated and the architects may be seen as "arrogant" and "inflexible" (Siva & London, 2011).

Numerous factors contribute to a healthy and sustainable relationship between architectural professionals and their clients. Among them, effective communication serves an important role in maintaining such a relationship (Ahmad et al., 2012). Considering all the aspects of communication processes, a vital link is the presentation of the design progress, in the form of drawings, models or renderings. However, successfully visualizing the design can be a challenging task for many (Salisbury, 1998). The selection of media is usually important – the goal of an architect is to find the best way to present the project and avoid common pitfalls caused by misinterpretation, thus better facilitating the process and preventing disputes if the client cannot understand certain aspects of the design. As an example, Pressman used an actual architect-client scenario to demonstrate the importance of choosing the right media in order to better explain the intentions and rationale for a building project. (Pressman, 1995).

2.2 Different Kinds of Architectural Models

Model is a flexible term that applies to a large range of real and virtual objects (Morris, 2006). Its form is undefined, from so-called trash models to highly detailed, realistic 3-D printed models, or even full-scale mock ups of rooms.

However, no matter which form an architectural model takes, there are a number of objectives - it should represent a room, building or a group of buildings, it should be at a smaller scale than the actual structures, and it should help people understand the architectural idea (Morris, 2006).

Physical models are proven media for communicating architects' ideas, particularly to non-architects, because of their physical immediacy (Moon, 2005). Using a physical model is believed to be an effective medium for predicting the real environment (Seaton & Collins, 1972; Feimer 1984).

As technology has evolved, designers have begun to use software programs to present designs virtually. The validity of those virtual tools has been studied by multiple researchers (Foreman, 2003; Rahimian, 2011). However, since digital models take so many different variations on so many different platforms, it is difficult to determine their effectiveness in general.

A variety of modeling methods have been used in previous studies, ranging from traditional physically-based media to newer, digitally-based media. Not only have different modeling techniques been examined, but researchers have also explored other technological methods to present these models. The following list includes some commonly studied media and methods:

- Physical Model - traditional model construction. Typically, it is built by hand or with machinery assisting at certain levels; it is often built to a certain scale using materials such as wood, metal, paper and plastic. Newer technologies, such as 3-D printing, have also been developed, eliminating the need for human hands in the model construction process. A large array of literature focuses on the build, characteristics, and inherent quality of physical models; for example, some produced comprehensive guidebooks for the making of architectural models (Dunn, 2010; Mills, 2005), Busch (1990) discussed the power of models and how they help architects to communicate their ideas, whereas Abruzzo et al (2007) gathered a collection of articles discussing the possibilities of models and how they help architects explore meaning and context in their design processes.

- Computer Rendered Imagery - a method utilizing computer programs to generate three-dimensional architecture models. It presents the models in a two-dimensional medium; renderings can be either printed, or on screens. Uddin (1999) described renderings as “the techniques used to create images that are more realistic than straightforward line drawings.”
- Model Film and Model Video – Model Film is the presentation of a color film that simulates an eye-level auto tour with a scale model of the real environment and dynamic environmental conditions, and Model Video is a black and white version of the model film (Feimer, 1984). Those two media were used in Feimer’s study of how laypeople and design professionals understand architectural space.
- Desktop Virtual Environment (VE) - an interactive computer-generated 3-D model in which users can navigate and view from different angles. Since this technology is more affordable, a large number of software programs have been developed for different purposes. Numerous areas have adopted VE; for example, it has been used in area planning (Wanarat & Nuanwan, 2013; Wissen et al., 2008) and geometric modeling (Gomes & Velho, 2013; Agoston, 2005), to name two. Currently, this is a widely used medium by

architects in different aspects of design, such as thermal comfort design strategies (Yezioro & Shaviv, 1996).

- Immersive VE - a head-mounted display goggle that covers the participant's vision. A magnetic tracking device is used to help the participant navigate through or around the model (Schnabel & Kvan, 2003). This system has been developed by many researchers and it has a broad range of applications. For example, Persky conducted a literature review regarding its effectiveness in healthcare communication (Persky, 2011); Mavridou (2012) studied VE's effectiveness of scale perception in a set of virtual urban environments; Schnabel and Kvan (2003) used similar technology to examine people's understanding of three-dimensional blocks and their spatial relationships.
- Panorama - a theater with a cylindrically cured screen that covers almost 180 degrees and can fill the vision areas of the viewers. The panorama display has a wide range of simulation applications such as operation control simulation (Tang, et al., 2005) and its effectiveness in depth perception has been studied by Mullins (2006).
- Computer Aided Virtual Environment (CAVE) - a rectangular room with projected images on six sides. CAVE provides the viewer an immersive experience of a virtual environment; the viewer can also interact and move around the environment with a hand held electromagnetic tracking system (Mullins, 2006). CAVE is not a universally agreed upon name; similar applications can be found in facilities using different terminology, however,

the general principle and mechanism is similar. This technology has been applied in areas such as operational safety training (Yuen et al., 2010).

- Augmented Reality - a form of Virtual Environment that allows the user to see real environments, while superimposing virtual objects upon them (Azuma, 1997). This technology is being developed in areas such as health care environments (Albrecht 2013) and education (Cuendet et al., 2013). Its application in architecture, engineering and construction industries is also being explored. For example, Irizarry et al. proposed a method to improve the decision making process with a mobile augmented reality tool (Irizarry et al., 2013), and researchers have also examined its application in real environments to enhance the level of immersive experience in architecture and urban planning solutions (Cirulis & Brigmanis, 2013).

As the list suggests, many types of models have been developed and studied intensively by architects, psychologists, computer scientists and educators. There are even more media on the horizon. With newer technologies, such as more advanced three-dimensional displays, namely the Mixed Polarization 3D (AkÅit, 2012), and haptic Virtual Environment (Hale et al., 2009), we can expect this list to expand in the future.

2.3 Understanding the Space via Media

No matter which medium a designer chooses, the aim is to use it to represent the real environment, e.g., a future community garden, or a to-be-built office complex. After gathering feedback from clients and future occupants, the designer then analyzes and deploys strategies to improve the design. These information exchange sessions usually occur multiple times during each design project. All these actions are based on one assumption: the medium of choice can successfully represent the actual architectural space.

2.3.1 The Theory of Spatial Perception

Researchers have employed both methodological and theoretical methods to explain people's perception of space (Caird & Hancock, 1992). Methodologies and measurements have been developed on this subject matter and one of the primary focuses is the estimated distance of an object from the viewer (Gilinsky, 1951).

Haber described the perceived spatial layout as the "perception of the locations of the objects in the scene: their placement with respect to the ground surface; to one another; to the boundaries of the scene; and to the observer" (Haber, 1985, p. 01). He stressed the importance of perceived layout as an essential factor in helping people to navigate through different spaces.

However, people do not perceive model environments as accurately as reality. Studies have shown that people usually blend the geometric layout with their own potential to interact with it, resulting in a different understanding of the actual layout (Bridgeman & Hoover, 2008). Also, people's own body size may determine their perceived size of the environment (Hoort, 2011).

2.3.2 Representation versus Reality

How different media perform against the real environment is a topic of interest among researchers, and different aspects of simulated environments have been examined, including lighting quality, emotional quality, spatial cognition and so on, which are described below in more detail.

2.3.2.1 Physical Media and Reality

Traditional media, including those presented in both three-dimensional and two-dimensional forms, generally appear to have similar results comparing to the real environment. For example, Lau (1970) carried out a study comparing people's evaluation of lighting quality using scale physical models. He found that scale models worked very well under his test conditions for comparison to the real environment. Another experiment carried out by Lau (1973) examined how people evaluate a scale model against the full-size mockup. The results showed there was a general similarity between these two. Stamps (1993b) found that working drawings are an effective medium that correlates well with actual buildings. Seaton and Collins (1972) conducted a study comparing real buildings on a university campus with physical models, color photographs and black and white photographs. The variables tested were a series of emotional scales described by adjectives, including peaceful, strong, dynamic, orderly, pleasing, etc. Their results indicated that the qualities that buildings impart to viewers are generally similar across the different media they tested. However, they also raised the question that no matter which simulation is selected, it cannot be fully congruent with the physical, full-scale reality.

2.3.2.2 Digital Media and Reality

Digital media has gained value for its applications in spatial cognition research (Pe′ruch et al, 2000). One area that has been examined intensively is spatial orientation.

Certain researchers have found that Virtual Environment is an effective medium to study people's navigation behavior compared to the traditional use of the real environment (Waller, 2004; Gyselinck et al, 2013).

Besides spatial abilities, studies have used VE to test other measures, including the audit of pedestrian safety, traffic, parking, and infrastructure, against the real environment. The results showed a high level of concordance between the VE and the actual environment (Badland et al., 2010; Rundle et al., 2011).

2.4 Comparison Between Media

Ever since the dawn of the digital era, advantages and disadvantages of both physical models and digital models as presentation media have been discussed, debated and revealed in the day-to-day practice of architectural design. Common beliefs that support the use of physical models include their ease of communication, as "the first manifestation of a design that a lay person can readily apprehend" (Morris, 2006). They represent a universal language that is understood by everybody, and more readily comprehended than computer imagery (Moon, 2005).

Digital models, on the other hand, appeal to designers for their ease of revision, and they may help lower production time and cost. They are also much easier to archive compared to physical models (Morris, 2006). Given current technology, photo-realistic imagery is much easier to achieve with a digital environment than with physically constructed models.

A review of the studies about those two types of media is discussed in more detail below.

2.4.1 Physical Media

As a fully mature medium, the use of physical models has a long history continuing into the present. Not only have they been used to convey ideas to clients and the public, they have also served the purpose for studying space, form and structure during the design phase. For example, Renaissance architect Brunelleschi was known for his scale model that demonstrated the feasibility of masonry structural design for his to-be-built dome in Florence (King, 2000). Antoni Gaudí also used hanging models to design masonry and concrete structures (Huerta, 2006). Modern architect Louis Kahn also used physical models intensively in many of his projects in the form of study presentation models (Gast, 1999). These cases only comprise a very small portion of the myriad of architects across history who used models as their prominent means of design and communication. As a matter of fact, making physical models has been stressed so much in both education and practice that it is almost mandatory for any designer on any project.

2.4.1.1 Advantages of Physical Media

The benefits of physical models have been discussed by many. More than a narrative record of a building, it has an artistic existence independent of the project it presents (Eisenman, 1981). For example, the tactile properties of physical models are an important advantage that modern computer-aided models lack (Maze, 2002). Also, Morris (2006) claims that virtual reality is actually much less virtual than physical models, since the physical model allows for "serendipity of bricolage and the 'virtual' creativity of chance", while the digital model is characterized, and usually constrained, by limitations. The ability of physical models to help people determine the size of objects, or the absolute distance, is superior to those presented in digital format (Henry & Furness, 1993; Bliss et al, 1997; Wilson, 1997; Mullins, 2006). A recent study pointed out that people have a much better estimate of building size when looking at a 3-D printed model than when looking at a digital model projected on a computer screen (Sun et al, 2013).

2.4.2 Digital Media

A few decades ago, the application of computers to architectural design began to emerge and challenged the convention of architectural design practice. When the computer was first adopted in the field of architecture, its applications were primarily focused on 2-D tasks like plotting floor plans, and the machines were large and clumsy. But since then, the fast paced development of technology has gradually taken over more and more duties that used to be performed manually. With the launch of the software package - FormZ digital 3-D models -- in 1989, computer-generated models began to reach a broad-based market (Morris, 2006) and a large number of architecture schools adopted the software in the 1990s (Uddin, 1999). Nowadays, we are experiencing a great boom in the development of software packages that offer virtual modeling systems across different platforms and display media (Rheingold, 1991; Krueger, 1991; Durlach & Mavor 1995; Arthur, 1997). Additionally, due to the imperfection of certain new technologies, challenges still exist, such as the high skill level needed to operate the programs, counter-intuitive human-machine interfaces, and limitations in software and graphic renderings (Dunleavy et al, 2009; Moum, 2010; Wu, 2012).

2.4.2.1 Advantages of Digital Media

From a practicality standpoint, digital media are usually cheaper to produce and easier modify, thus they may save production time (Morris, 2006), which in turn saves operation costs for architects

Empirical researchers have focused their attention on this subject matter, approaching the topic from other perspectives. As discussed previously, in terms of spatial orientation, studies have shown that computer models have an advantage over physical models in spatial navigation and perception of the relative distance between objects. For example, in an experiment of way finding tasks in a school environment, better accuracy was achieved by children who studied the route in a 3-D digital model versus those who studied physical models (Foreman & Stanton, 2003). In another study of spatial abilities in a math learning environment, researchers found that students performed better in understanding shape rotations using VE versus using physical manipulatives (Baki et al., 2011). But they also argued that the proper use and design of media is important for each medium to achieve optimum effects.

2.5 Summary

The relative effectiveness of presentation media has been examined by many researchers. Currently, comparisons of each medium against the real environment have been studied, and the comparison between different media has also been studied. Among those, the commonly compared aspect across the physical architectural models and digital architectural models is their effectiveness in learning, space orientation and way-finding tasks.

Meanwhile, previous research studies have suggested that design professionals differ from the general public in the perception and understanding of certain representation methods (e.g. Feimer, 1984; Gharai, 2000; Nasar, 2008). The "spatial abstraction gap," as pointed out by Mullins (2006), refers to laypeople's negative evaluations of digital models, as opposed to drawings and physical models, since people without professional training tend to have difficulty translating virtual models to the physical world. To successfully predict people’s perceptions of the real world, it is important for design professionals to better understand the general public's abilities and preferences, in order to provide the right models.

CHAPTER III

QUALITATIVE METHODOLOGY: INTERVIEWS

3.1 Overview

Qualitative methods address naturally occurring events and focus on studying those events in all their complexity (Leedy & Ormrod, 2005). The main purpose of this part of the study was to investigate project design communication routines between architects and clients, especially the choices made with regards to media and how clients react to them. The qualitative part of this research added another dimension of perspectives to the quantitative data alone.

The qualitative part of this study was characterized by in-depth, one-on-one interviews with eight architects who had rich experiences in design practice. The nature of qualitative research, research design, and process are further explained below in detail.

3.2 The Nature of Qualitative Research

Qualitative researchers recognize that the subjects of inquiry have many dimensions. Unlike quantitative approaches, which are characterized by the belief that the observations should be affected as little as possible by subjectivity, qualitative methodology embraces the notion of perceptions and impressions (Leedy & Ormrod, 2005). In the context of social study, which involves interpersonal relationships, such a well-controlled environment may not be desirable nor possible (Eisner, 1998; Wolcott, 1994).

3.3 Phenomenological Study

Leedy & Ormrod (2005) conclude that the phenomenological study attempts to explore people's understanding and perspectives of a situation. They also claim:

> In some cases, the researcher has had personal experience related to the phenomenon in question and wants to gain a better understanding of the experiences of others. By looking at multiple perspectives on the same situation, the researcher can then make some generalization of what something is like from an insider's perspective. (p.139)

With the involvement in architectural design practice, I intend to gather a broader spectrum of perspectives by interviewing architects regarding the research questions listed in Chapter 1. Thus, carrying out a phenomenological study becomes the preferred choice for such type of inquiry.

3.4 Characteristics of This Study

During the course of the interviews, I, the inquirer, acted as an internal component of the process; the aim was to create frequent and meaningful interactions between the respondents and myself. Mutual influencing also became a natural part of the study, since the same starting topic for different respondents often leads to vastly different conversations, and the active acquisition of knowledge based on an adaptive and emergent design can influence respondents to provide an even broader spectrum of information. At this point in the research, the interviewee and interviewer became integral parts of the conversation, achieving a state of "mutual simultaneous shaping" (Lincoln & Guba, 1985, p.38).

In terms of causal relationships, it was not my aim to determine whether different choices in media caused clients' different levels of understanding and/or preferences, or whether clients' understandability and preferences influenced their architects' choices regarding different types of media. Rather, the aim was to investigate the nature of the architect-client relationship and interaction in each particular time and context, in order to form a more holistic view of the subject matter.

Perspectives, social/cultural norms and personal norms can all affect the outcome of an inquiry (Lincoln & Guba, 1985). This study acknowledged the inseparable influence of value from both the inquirer and the interviewee, since value dictates so many aspects of life and a value-free environment conflicts with the general state of being human. Being value-bound, hence, can be seen as a limitation of inquiry itself.

3.5 Research Design

This section presents the design and procedure of the quantitative part of the study. A series of topics were discussed including the research instrument, subject selection process, interview process and questions, data collection methods, and data analysis techniques.

3.5.1 The Instrument

One of the distinguished characteristics that qualitative research bears is the use of human beings as an instrument. Compared to other instruments, Lincoln and Guba (1985) listed several unique advantages of the human instrument:

Responsiveness, which means that humans are able to interact with a research environment and respond to it. This is particularly apparent in the interview sessions in this research, in which the interviewer's involvement in the conversation was essential to keeping the process flowing smoothly.

Adaptability, which means that humans are adaptable to different situations and collect information about multiple factors at multiple levels. In many cases during the interview sessions with architects, new ideas and information started to emerge and the process began to divert from the main focus. On such occasions the interviewer was able to quickly evaluate the situation, make proper adjustments, and collect information from different perspectives.

Holistic emphasis, which means that no other instrument but a human has the ability to grasp holistic information. It was not surprising that each interview session was characterized by the beliefs and values of the subject of inquiry. Besides, each example the interviewee gave was characterized by its particular context. It was the interviewer's job to grasp the holistic idea and synthesize different aspects from different interviews to form a holistic picture of the subject matter.

Knowledge base expansion, which means that the human instrument has the ability to work with propositional and tacit knowledge at the same time. As the interviews progressed, the interviewer was able to gain knowledge from different but simultaneous aspects.

Processual immediacy, which means that humans are capable of processing data as soon as the data are available, and can generate new hypotheses on site. As an example, when an architect introduced a particular model he used during some of his client meetings, the interviewer was able immediately to absorb the information and generate new conversation topics regarding the details of this model.

Opportunities for clarification and summarization, which means humans can quickly summarize data and make clarifications for subjects. The ability to summarize and clarify was applied in every interview session. Oftentimes, the interviewer summarized the information after an architect finished describing an experience. Also, when certain potentially interesting conversations only scratched the surface, the interviewer was able to identify such moments and ask the architect to clarify them in greater detail.

Opportunities to explore atypical or idiosyncratic responses, which means humans can identify and analyze atypical responses which might otherwise be considered useless by an ordinary instrument. This action can often lead to a higher level of understanding. There were circumstances in which architects provided information that seemed irrelevant to the topic, but under scrutiny such moments turned out to be valuable supplements to the focus of the interview; it was only the human instrument that was able to identify such information and make use of it.

3.5.2 Subjects

The main focus of this research study was to understand interactions among architects and clients, so potential participants needed to have a rich experiences in design practice. Being a registered architect in the United States was also a criterion since it ensured that each participant had gone through each stage of the architectural design practice and had a comprehensive understanding of the profession.

Based on this principle, a purposive sampling method was chosen to select the architects to be interviewed. It is a nonrandom way of choosing respondents and was not meant to be representative, but instead meant to “maximize the scope and range of [the] information obtained” (Lincoln & Guba, 1985, p. 224).

The first three interviewees were individuals chosen from my personal contacts who also fit the criteria. Based on their referrals, six more interviewees were contacted personally or via formal email invitations. The personal contacts and secondary referrals turned out to be highly effective, which led to a very high response rate; eight out of nine architects invited agreed to participate in the interview sessions.

3.5.3 Interviews

In-depth interviewing served an important role in gaining knowledge of the subject matter. Besides being a technique, the process and experience itself was a valuable product derived from being part of the inquiry. This notion is elaborated upon by Paget:

> In-depth interviewing isn’t simply a technique or a vehicle for acquiring information; that is too narrow an understanding. It is a search procedure, grounded in a series of problems being investigated by a thinking subject. *Knowledge* in in-depth interviews means coming to understand, achieving a resolution of puzzlement. This is a dynamic process in any given interview and a cumulative process over a series of interviews. There is another aspect of the meaning of knowledge used here. Knowledge here means illuminating human experience: the complexity, opaqueness, and mystery of an essentially subjective species (Paget, 1999, pp. 101).

As discussed above, the focus of the interviews was an understanding of the interactions between architects and their clients. However, it is a characteristic of the naturalistic inquiry that a research focus may change, and the boundaries blurred and altered. As the interviews went on, the initial focus became somewhat obsolete and inadequate. Thus, more topics emerged and were adapted to the newly gathered information.

In the early stages of this research study, a broad interview protocol was developed with a series of topics that needed to be covered in each session. Since the interviews were only semi-structured, after covering each topic in the list interviewees were allowed to express freely any additional ideas and experiences they felt might be relevant. These more casual and engaging conversations were also intended to expand the spectrum of the investigation. Some of the original topics that were covered during the interviews include:

- How many types of models have you made/used during your practice?
- What is your opinion of the effectiveness of digital models versus physical models?
- During the Schematic Design / Design Development phase of a project, which type of model do you think better helps a client to understand the project?
- When interacting with your clients, do they show particular interest towards one type of model over another? Can you give specific examples?
- Why do you think clients prefer one model over another (if they do)?

These topics merely formed a basic framework for the interviews. As each session started to flow and unfold, new questions emerged and filled in any gaps. Many architects expressed their interest in the making and characteristics of the different types of models they used, so more questions were added to focus on this area, including:

- Do you think different levels of model detail affect your clients' levels of understanding?
- Is there a level of detail that can be marked as a threshold beyond which people begin appreciating the model?
- Do you think scale affects people's levels of understanding?
- What about model materials? Do you think the choice of material affects people's understanding and preferences?
- Do you think different model types should be used at different design stages?

These are just a few examples of the questions that emerged during the interview sessions. As different architects showed interest in different aspects, many new questions were posed to them on a large array of topics. Details regarding and analysis of the conversations will be covered in greater depth in the Data Analysis section.

3.5.4 Data Collection

Two sources of data were accessed to collect information during the qualitative sessions.

The first and most important source was the content derived directly from the conversations engaged in during the interviews. A total of eight interviews were conducted in three cities in Texas, in the United States. Most of the interviews took place in the architects' places of work, including personal offices and meeting rooms, with a few being held at community and private gardens. The interviews lasted from 30 to 90 minutes. With the consent of the architects, the conversations were audio recorded with a digital recording device placed on a visible surface and pointing at the interviewee.

Names, places, project names and locations mentioned during the interviews were kept confidential to respect the privacy of the interviewees.

As is the nature of naturalistic interviews, the original questions were merely a framework for the inquiry. This open-endedness enabled the conversation to expand in different directions, thus allowing a richer level of content to unfold. As a result, the interview sessions constantly evolved as more and more questions emerged; thus, it was difficult to control the time of each interview session (Lincoln & Guba, 1985).

The second source of data was the observations of the interviewees, including non-verbal cues such as their expressions, manners and gestures. This was also an important source of information to support the verbal data. As described by Guba and Lincoln (1981):

> Observation… maximizes the inquirer's ability to grasp motives, beliefs, concerns, interests, unconscious behaviors, customs, and the like; observation … allows the inquirer to see the world at his subjects see it, to live in their time frames, to capture the phenomenon in and on its own terms, and to grasp the culture in its own natural, ongoing environment; observation … provides the inquirer with access to the emotional reactions of the group introspectively – that is, in a real sense it permits the observer to use himself as a data source; and observation … allows the observer to build on tacit knowledge, both his own and that of members of the group. (p.193)

The observations were kept in the form of field notes in a reflexive journal, which is an important component in triangulating the information (Lincoln & Guba, 1985). When combined with verbal cues, these notes helped me to better identify the interviewees' attitudes toward certain aspects of the issue; for example, a gesture of emphasis when speaking a word is difficult to identify solely by listening to the recordings.

3.5.5 Data Analysis

After the interviews, the audio recordings were transcribed into text files. The first step of the analysis was the process of unitizing, which is when a researcher breaks down the contents of the data into the smallest pieces of information on the subject matter that can be understood without additional information (Lindoln & Guba, 1985). To carry out the unitizing task, chunks of text from interviews were broken down into words, sentences and paragraphs based on the aforementioned rule. Each letter-sized page was split into two 8.5" x 5.5" cards, with each card containing one piece of information. The cards were then printed out and assigned the letters A through H, identifying each interviewee.

The second step was the categorizing process. This process was performed following the instructions described by Creswell (1998), as well as Lincoln and Guba (1985). All cards were stacked in a pile and I began with the topmost card. After becoming familiar with its content, I set the card aside. The second card was dealt with in a similar fashion. By tacit knowledge, if it "looked/felt like" (Lincoln & Guba, 1985) the first card then it was placed in the same stack as the first card; if not, it was placed in a stack separate from that of the first card. After a certain amount of cards were sorted, the larger stacks were revisited, and broken down if possible. Based upon their common information, category names were then created for the stacks and written on folded mat board (used as category tags); these tags were laid on the floor in front of each stack, facing towards me. Any future cards that belonged to those categories were stacked behind the category tags. This process continued until the last card was sorted.

During the process, as more information accumulated inside each category, adjustments to the category descriptions were required. Sometimes the descriptions needed to be extended to accommodate a broader spectrum of the subject, and other times a certain category was more explicit once it was divided into sub-categories. Also, there were several occasions in which the information contained on a card belonged to more than one category. Such cards were then duplicated and included in all qualifying stacks.

The categorization process came to an end when there were no more new categories to be added into the array of existing categories. At this point, there were still a great many cards that did not have a place in any of the stacks. They were examined again and in some cases, a card was able to be fit into a category that was overlooked previously. Also, those cards that were identified as irrelevant were discarded.

3.5.6 Summary

It is the nature of qualitative research methods that a researcher does not know what will happen ahead of time; therefore, the methodology tends to evolve and develop over the course of the investigation (Lincoln & Guba, 1985). This condition indicates that new information and discoveries might emerge as the inquiry goes forward, and adjustments in methodology may be necessary to better adapt to new situations. Since the study focused on people's evaluations, preferences and attitudes towards a particular phenomenon, semi-structured, open-ended interview sessions were appropriate to accommodate the changing nature of relativity. This was all part of the phenomenological study methodology and was crucial for creating the flexibility necessary to allow the research to emerge, flow, cascade and unfold.

CHAPTER IV

QUALITATIVE DATA ANALYSIS

4.1 Introduction

This chapter presents the content of the interviews with the architects. These data were categorized based on the methodology discussed in the previous chapter.

This chapter includes four categories: the types of media, the characteristics of the media, physical versus digital models in practice, the art of marketing, and the model making and the design state of mind. Each category consists of several sub-categories.

4.2 The Types of Media

How architects use models in their practice and what types of models they prefer are two of the main focuses of this part of the study. The interviews revealed that architects have used many forms of physical and digital models, and oftentimes use a combination of different models from different media to serve their purposes, either for their own design study or to convey information to their clients. The experiences of these architects with each of the types of models is summarized in this section.

4.2.1 Physical Models

Physical models were widely used among all architects interviewed, and their forms varied greatly depending upon a project's phases and needs. Different levels of sophistication were chosen to accommodate different design stages and scenarios.

Some of the architects that participated in the interviews adopted physical representation media in the early stages of design, even before the preliminary building form took shape. These gaming tools were typically gaming models used for planning purposes, with schematic blocks representing rooms and departments. These model pieces were not only used to convey architects' concepts regarding the design space, but also helped to engage clients in the design process, thereby enhancing their understanding of the projects. According to interviewees C and E:

> … my work begins even earlier so that when you are doing planning rather than using only drawings of the plans, I used the process called gaming, in which you have a board and you actually cut out to scale [those] pieces of paper – in my case colored paper that have some meanings to the colors. With the client you move it around on the board until you arrived at a version of the plan…

> … so before we would draw the drawings we were using a model – two-dimensional model – with the client… and with their involvement to increase their understanding of what was happening and then subsequently, when we produced our drawings, they had a much higher understanding of what was in the drawings, because they have been involved in this gaming process…

During master planning, physical models were one of the primary tools used for information exchange in the architect-client relationship. Massing models were used to effectively present site information, preliminary design ideas, relationships with surrounding environments, etc. The massing models were easily moved around so different ideas could be explored. According to Architect H, one merit of massing models is that they can be considered a low-cost, fast but effective way of communication:

> …something [where] we can move them around easily, we can come up with different configurations very quickly, and there isn't a whole lot of time put into it, because you know they are not going to last…

Massing models can be produced at different levels of complexity. They can be very schematic and small scale, or a bit more detailed and in larger formats. Architect H notes that:

> … you can have a dozen of those, or even more, and at any scales. Those all vary based on what you are trying to explain. The next set of massing models will end up being a specific scale, medium detail, so it could be like 8th, or it could be 16th, depending on the scale of the building and it will be relative to that, and then… the surrounding buildings could just be boxes…

Massing models can take on other forms, according to some architects. Plexiglass models were used to represent floor plates in conceptual massing diagrams, so the floor geometries could be altered as well as the number of floors and composition of the building. Architect C advocated for the use of plexiglass:

> …so I would use clear plexiglass, sit on clear cylinder spacers so you could have a stack of clear plexiglass… you can tell in the stacking diagram of how the building is going to be designed…

Physical models were described as becoming more sophisticated as the designs progressed. When the building is taking shape and no big changes to the exterior form are expected, models with fenestrations, materials, color and other details may be introduced by architects. At this stage of the design, a model might become more defined and refined, almost to the quality of a miniature of the completed building. Sometimes clients are interested in the selection of exterior materials (e.g., stone versus wood panels). In these cases, architects can create models with interchangeable panels for particular areas, and apply similar colors and textures to it to mimic the actual materials.

Interviewees suggested that a maximum level of detail and sophistication occurs when a marketing model is made in which detailed components are precisely crafted to achieve the ultimate look of the model. Physical models used for marketing are the most expensive to make and usually are displayed for donors and potential investors. Architect B stated that the marketing model is:

> … one that is extremely detailed, which has joints or brackets, something laser cut, [and you] add more materials and colors to it… If clients want to do marketing, when people see it, they will say: "I know exactly what that is."

4.2.2 Digital Models

The forms of digital models vary. Architects have long been using numerous kinds of software program to produce digital models. Among them, one of the most commonly used program has been SketchUp, since it is easy to use and can quickly generate simple geometries. Unlike some other software products, SketchUp can display relatively more realistic models in real time and doesn't consume extensive hardware resources. The interviewees indicated that architects usually bring a SketchUp model to their client meetings and believe that such models are more effective than still renderings.

SketchUp also suits a wide range of design stages. Most architects interviewed have used it from the conceptual design stage all the way through design development. The program includes a basic animation function that has also been used by architects for preliminary design concept presentations.

Architect G also mentioned that Revit is another commonly used software program. As a Building Information Modeling (BIM) tool it mainly is used by architects for design and drafting purposes. However, the rendering engine embedded in this program can produce high quality photorealistic renderings, which is a welcome feature. Such renderings are usually produced in the later design stages.

There also are programs that specifically produce renderings and flyby animations, such as Lumion. In recent years, some of the interviewees have begun to use such programs to create better presentation materials in house as a supplement to their conventional presentation media. These programs can be of great help to architects in explaining their design ideas while also, in the long run, saving the cost of outsourcing.

4.2.3 Something Unconventional

4.2.3.1 Physical Models

Beyond conventional physical and digital models that can be built in a shop or studio, other forms of models have also been explored by architects, including full-sized mockups and immersive digital environments.

One of the more commonly used full-sized mockups is built on site. Usually. Such mockups represent a façade section of the building and demonstrate alternative materials. For example, it may be hard to visualize how a particular type of glass will look under different weather conditions; the effects of its reflectivity and transparency are difficult to simulate using computer software, and it is impossible to build a scale model of the glass to the same specifications. The full-sized mockup enables architects and clients see how optional materials look and perform in real conditions. According to Architect G:

> A lot of projects… you need to have a mockup, so that's a physical representation of the project where materials come together, because everybody wants to see how the details are and what the materials are like…
>
> A mockup, it's built, it's out there, client can walk by anytime and look at it and sign off on that: "yes I like this and I like that".

There are other kinds of full-sized mockup models. One interviewee participated in numerous projects that involved full-sized mockup models of patient rooms. Those rooms were fabricated on a full-sized scale with the actual materials, and clients were invited to walk in and experience the space in real life instead of looking at a miniature version of it or a digital model on a computer screen. Such full-sized mockups are most appropriate if the space to be designed is critical for user convenience and wellbeing, especially in healthcare environments.

Full scale mockups can go even further and become fully functional; this is where the boundary between models and real built environments begins to blur. An example given by Architect C was a hospital that built room models of their future designs and tested them out before the facility went into the renovation process. Doing this allowed physicians, nurses, and patients (as well as architects) to take their time in identifying problems associated with the new designs, and still have the opportunity to make adjustments. When describing this process, Architect C informed us that the hospital:

> …built rooms in their existing hospital that were exactly what they were planning to build, so they were able to have real patients in real rooms and compare them to the existing ones to do study that to identify what they want… So that's probably the most extreme version of full-scale mockup… because the patient room was going to be repeated multiple times of the project, and so if they make a mistake, it would be repeated multiple times.

4.2.3.2 Digital Models

In terms of digital models, new technology has opened up new possibilities to view the computer generated models in different ways. For example, immersive virtual environments were used by Architects B and F to enhance the experience of the spaces in a proposed project. An immersive lab was hosted by the university where the project was located. A three dimensional digital model was provided by the design firm and converted to support the simulation program. Viewers were invited into a cubic room with back side projectors on each of the room's interior faces. The contents of each projector were aligned to produce a continuously surrounding digital envelope that allowed the viewers to look anywhere without leaving the virtual environment. The model could be controlled by technicians so viewers could "walk" inside the model freely and explore the different spaces at will.

4.3 The Characteristics of Media

The interviewees were very interested in the characteristics of the media used, and expressed many thoughts and insights to support their ideas. With their years of practice and the numerous clients with whom they have dealt, the subjects offered a variety of observations about the characteristics of the models and the way they presented them.

4.3.1 Physical Models Versus Digital Models

It was difficult to discuss physical or digital models without referencing one or the other; the interviewees compared each type of model's merits and detractions in a parallel manner. The subcategories in this section discussing the virtues and disadvantages of each type were not intended to be mutually exclusive.

4.3.1.1 Merits of Physical Models

In general, the architects believed physical models to be a more effective medium for use in front of their clients. People enjoyed the "intimacy" created, and the design concepts seemed easier for them to grasp when presented with physical models. Digital models, although they had many characteristics that were difficult to replicate in the physical world, were still considered less "tangible" by some of the architects. Architect C reflected:

> … Even digital models that allow you to move around as if they were seeing the physical model from different perspectives – above and below and so on – today's computer ability isn't so hard [to do], but it still isn't as tangible as the physical model, which you can do the same movement – tilting and angling by simply holding it up… so the ability to change perspective and see it from more than one angle I believe is probably part of how the brain reaches the point where it thinks it understands…

Interviewees expressed that another advantage of physical models was that the viewer and the model are in the same physical environment, whereas the digital models all sit in their own "constructed" world; viewers needed to work harder in order to put themselves inside the virtual environment. Specifically, Architect H stated:

> …I think the clients understand physical models better because they are experiencing in the same environment they are in instead of the imaginary

> space; the digital model, you look at something, you imagine the space and environment as what is shown on the screen…

Some interviewees raised the point that in terms of the color and material differences between physical and digital models, physical models stand out when the same conditions are applied. A digital massing model is much more difficult to understand than a physical massing model, given the same single-color appearances. Architect H noted the need to add more detail to a digital model in order to give people a better understanding:

> …if clients could see it and hold it before them I think it's a bit easier for them to understand… It's much harder for people to understand what it is if you show them solid grey 3-D models.

Another example, given by Architect B, involved a lobby space design. A conceptual digital section model was made for client meetings, but the surfaces were kept white and there was no application of texture or material. It turned out that clients had great deal of trouble understanding the space and its inherit characteristics. Aware that this might be an issue, Architect B also provided a detailed section model of the same space (made of ABS plastic) to supplement their slide presentation. Despite the fact that this physical model was also all white, once viewing the physical model the clients were able to grasp the concept instantaneously.

One characteristic of physical models that differs from digital models, as expressed by Architect E, is that physical models are a distillation of reality which allows people to imagine beyond what is represented; digital models are usually seen as something fixed and "real," and people tend to understand them as renderings of reality. According to Architect H:

> …in my school we did basswood models, I can take it to my parents and they understand what it is. I could show them 3-D images and if it doesn't have all the materials done, it's harder for them to understand… they have to see the materiality with the form [together]…if none of them has material, I think it's still harder for them to understand what everything is. While you can do a solid color model – a physical model – they know this isn't real because they can pick it up in their hands, and they know, as soon as they see the model, they know this isn't real, so their imagination can go, whereas digital models are harder for their imagination to go, to take over.

Many of the architects noted that the life of a physical model doesn't end when the presentation is over. It can be appreciated in an ongoing fashion, as its value transforms into a type of art and statement. It can remain in the client's office as a display for his/her guests, or a focus of discussion during lunchtime.

4.3.1.2 Caveats of Physical Models

However, physical models aren't perfect. Sometimes, depending upon the level of detail, certain early-stage massing models still required architects to put forth some effort to fully explain their designs before their clients were fully able to grasp the concepts. According to Architect A:

> … the massing models… once they understand what it is, what it represents, they are able to see it, reposition it….

Interviewees observed that the amount of time taken to study and build physical models might also be problematic. Exploring options using digital tools was much faster and more productive under such circumstances. Furthermore, it took a prohibitively greater amount of effort to achieve a sophistication of detail and materiality in physical models, whereas constructing and applying photorealistic materials in a software environment was relatively easy.

Architect B found that the demanding market and clients may also prevent architects from exploring and presenting ideas using physical models, even when they want to:

> The thing I appreciated most about the digital models is the ability for a quick study. We can do a lot more… it takes a lot more time to build physical models…One of the reasons we have to shift to digital technology more than building models is because our clients are demanding such a fast pace for project delivery that we didn't really have the time in the design to sit down and build models…

4.3.1.3 Merits of Digital Models

The architects who participated in the interviews had mixed attitudes towards digital models. It was generally agreed that digital models were more flexible, cheaper and usually easier to produce, and they worked well in front of their clients under many circumstances.

As technology advances, buildings are more and more able to take forms with complicated curvatures and surfaces that involve customized components for fabrication purposes. The interviewees frequently noted the advantage of speed in digital models. Software programs such as Revit allow architects to design complex geometries with adaptive materials and components that can automatically transform themselves to fit new situations, if and when a design changes. The time and effort spent visualizing these complex geometries were much less than that which would have been required to build physical models.

Another advantage to digital models is that they are easier to store and transfer. Shipping a physical model to another city can make architects nervous because the delicate components can easily be damaged by rough handling and the vibrations in a plane's cargo bay. Architects sometimes carry glue in case something happens to their models.

The aforementioned immersive environment also received positive reviews from clients, according to Architect F. Such an environment is preferred by clients because they are able to look around, see the floor material under their feet, etc., and the environment makes it is easy for them to understand double-volume spaces (more so than when looking at a computer screen).

4.3.1.4 Caveats of Digital Models

Other than the disadvantages discussed previously when comparing digital models to physical models, architects also expressed other concerns. For example, one can distort the views to "manipulate" how a space looks on the display, as if the space is being viewed through a wide-angle lens. Architects B and H were concerned that the ability to change perspectives might cause the spaces to be dishonestly presented:

> …you could manipulate the view to make acute angle, maybe a fisheye, you can do a forced perspective, which distorts reality to where you can never see something physically, but you can simulate that in 3-D world. So it's kind of like lying.

> … [the space] looks very big because it's a super wide angle view, it makes it feel like a giant space. Now you [look at] the model, it's still a big space but is not like that in the rendering…

Immersive environments, which received positive reviews from some interviewees, is still an emergent technology and most designers have at best limited access; there are currently only a few sites that host this kind of laboratory, and it is costly. To display such large images requires extremely powerful computers and the image quality produced by current graphics engine is still less than desirable. Architect H found this challenging:

> … if you're looking for money from donors, you cannot tell someone: "Meet me over here, we can walk through this thing." Because sometimes they are taking money from… people who were really busy, who don't have time to do this. "You want my money? Let me see what it looks like, bring me something."

4.3.2 Design with Models

Of course, architects don't solely make models to show to their clients. They also use models themselves, to help with their own design process. As a result, all the interviewees were trained in school to make both physical and digital models.

Many of the architects interviewed preferred physical models because the interaction seemed more intuitive and the process sparked their creativity. They noticed a level of spontaneity that they rarely found when looking at a screen while fiddling with a mouse. Architects A and H remarked on the tactile process of making physical models; touching, rotating, moving and cutting were all sources of inspiration:

> …[doing physical models] is also the exploration of the architecture. So for me, I would prefer doing a physical model because I could explore, and I can do things quicker by exploring different options…

> …if I'm putting together something, like pieces of wood, sometimes those broken pieces will give you ideas. You can pick up a broken piece

> and hold it up, play around and thinking that might be an idea for something else. But digital model, you don't have this scrap piece, so you have to build something, you have to start coming up with an idea, test stuff out. For physical model, you just grab whatever is there, hold it up and trying it out. So that's the thing that I like, it isn't a totally blank slate all the time. It has stuff around to give you ideas.

Another benefit of physical models, mentioned by Architect E, was that by actually building it, one can have a deeper understanding of a building's structure, especially with more complex spaces. For example, how one plane meets another, and whether it is physically possible to build in full scale. When building something in the digital world, some architects found it easy to overlook certain structural limitations.

4.3.3 Sense of Scale

Understanding scale is an important aspect of understanding the built environment. As a result, can models give people the proper sense of how big an actual building is?

The answer to this question largely depends upon the type of media used and the way in which the information is presented. The interviewees believed that it was difficult to comprehend actual buildings by looking at conventionally-displayed digital models. Architect H's comment regarding digital models is as follows:

> …you thought you understand the scale – this is this big and this is this big – but then whenever the building is built and you walk out, to me it always seems like the building is much bigger than I imagined, because the building is only like the size of my two hands in the 3-D model. So that's the thing you can never ever get in a digital model, you never totally understand the scale of it…

One important factor for understanding scale is seeing something familiar for reference. Architect A mentioned that augmented reality could have great potential for allowing people to "see" their future buildings, since it would allow viewers to bring their phones or tablets, point them at a building site and see a 3-D model superimposed on it from the camera's view. With all the references around them, it would be much easier for people to understand the size of future buildings.

The possibilities with regards to digital simulation appear to be unlimited. The architects who were interviewed all agreed that digital technology was catching up quickly; its shortcomings might be less or nonexistent in the near future.

4.3.4 Sense of Control

Having the freedom to see wherever one wants to see was considered an important factor in people understanding a three-dimensional space. However, given the current technology, the human interface necessary to navigate one's view through a digital model was still far less intuitive than holding up a physical model and looking around.

In current practice, most architects still use traditional ways to present digital models, either by placing renderings in their slides, or by projecting interactive 3-D models onto screens and controlling the view (following their clients' directions). Architect B notes:

> …the difference between a digital model and a three-dimensional tactile physical model is the sense of control...Of course, I choose the perspective that I see when I see a physical model. In a digital rendering, you have chosen that for me, I have no control of that so I am reacting to

> what you’re showing to me. So you are limiting how I experience the building, the built environment.

According to Architect B, new technology (such as immersive environments) is still not widely used, so architects don’t have enough data regarding how much better their clients experiences might be when using these types of models. Generally, however, they had positive feelings toward future possibilities:

> If the digital environment gives more sense of control, for example the “4D” cube that’s called the immersive environment… I think that would be sort of a different digital environment because I can go in and I can actually see things and do things I want. I think that would be proper to give me more of the comparison because I can control it… I have control of what I see…

4.4 Physical Versus Digital in Practice

4.4.1 Client Stories

Architects always strive to carry with them the best presentation materials for each meeting, based on their own judgment calls. Sometimes, however, whether or not to bring a physical or digital model to a meeting can be a tricky decision, since it largely depends upon the client: are they more accustomed to computer technology? Or do they tend to rely on the tactile and tangible characteristics of physical models to better understand a design? The architects interviewed learned from experience that physical models generally do a better job, but in such relationships there was little room for failure. The stories told by these architects revealed the dynamics and complexity of the design practice.

One of the stories, shared by Architect F, happened during the economic recession when firms were struggling to keep their employees on the payroll. Large projects were scarce and when there was one, the competition was fierce. Aiming at winning a large commission, the architect and his team put special effort into producing some of the best presentation materials possible, including digital models and photorealistic renderings, together with a physical massing model that included the site and surrounding buildings. Tacit knowledge and past experience made the architect believe that a well-crafted physical model would be the most powerful tool in impressing the client. During the meeting, however, the architect found that instead of the physical model, the 3-D computer imagery was the center of discussion and almost everyone in the meeting was more interested in looking at the computer generated models than any of the other visual aids provided. He noted:

> …that's the first time that ever happened to me. We actually put a model on the table, and there [were] digital renderings and the clients gravitated to the renderings…

To understand possible causes for what happened, the architect further explained his analysis:

> …you know the [physical] model, with all the finesse, it's still not like a finished model which actually shows the architectural finish. It was a massing model. So for them, being able to visualize that is a building is hard, versus what they see in the picture…

As discussed previously by another architect, if a digital model and a physical model share the same level of materiality and detail, the physical model will usually work better. In this case, however, the digital model had the advantage of realistic texture and color that the physical model was lacking. He notes:

> …clients always take things LITERALLY. So you should be careful about how you manage that, how you present that information… I was just blown away.

The second story was just the opposite.

Architect B provided three design options for an iconic building. During the presentation, the architect first showed those digital models built by SketchUp, in his order of his preference. However, the client immediately rejected the first option that the architect liked the most. After viewing all three options, the architect prepared the physical models and began walking the client through the details of his design intent. The moment he brought out the physical model of the first option, his client showed a totally opposite reaction. When he looked at the physical model, he was instantly impressed by this design option.

> …then we put the model in front of him and he said: "Oh my God I love this!" He looked at it and said "I completely misunderstood this scheme!"… so this scheme would have not been selected if it wasn't for the physical model…

> ..it was such a moment of epiphany, it's like such a refreshing thing to see because it was a direct comparison between a SketchUp model looking exactly the same with the same level of detail – not a massing [model] – everything is drawn and it would have been rejected but it got selected because of the physical model.

This meeting influenced the architect to use physical models in his future interactions. He concluded:

> I'm not going to make these presentations using a SketchUp view. I know I won't be able to sell it…

4.4.2 Choices

Architects learned from these stories that it is unwise to assume a universal solution when selling products to different clients. The best practice is to produce both types of models at the same time. According to Architect B:

> … for me, the realization is that you really have to sort of learn and see what works for clients… every client is different, and therefore you really have to know them. You need to get to know them but in my personal opinion as a designer, that the best way to succeed, is probably a combination of these two. I don't think there is "this" versus "that", in my mind, when to apply what is really the question…

However, since digital models take many forms, for some architects there could still be a trial and error process before learning the best way to present to particular clients. Architect B elaborated further:

> Some clients, for example, acted extremely negative to SketchUp. I will show SketchUp models but they would reject it. They would say it looks horrible… they see that SketchUp doesn't have the quality or refinement so they are rejecting the design, and we kept changing the design and finally realized, this is not about design, it's just that they don't like this image! Then we went ahead and did a photorealistic rendering and boom - "Oh yeah we like it!" - But it's the same thing!

Beyond understanding clients, other factors can dominate the choice between a physical and digital model. Since making physical models is costly and time-consuming, project timelines and budgets can become the two deciding factors regarding whether architects put more emphasis on physical models or digital models. For small and simple projects, Architect H found it more economical to stick with computer generated models:

> If you have a small project, a couple thousand square feet, maybe a renovation, and you don't have much money on the project, and there is not a lot of high design in it, you're not going to do a physical model because you don't necessarily need to explain anything…

Sometimes the level of emphasis on physical models is also associated with the level of "importance" of the project, according to some architects. According to Architect G, a large project with "specialty pieces" of design is usually considered both a challenge and an opportunity; thus, architects direct their attention more toward making and studying physical models. Not only can models help clients better understand the project, but they also help architects refine and polish their design product.

4.4.3 Architects and Laypeople

All of the architects agreed that laypeople differed greatly from architectural professionals in terms of their ability to visualize a design through drawings. Two-dimensional drawings, including floor plans, were considered some of the worst media for them to grasp. Clients, in general, are not professionally trained in design or three-dimensional thinking, so architects must make extra effort not to overburden their clients with two-dimensional media. Architects B, C and E emphasize:

> I think absolutely there is a huge gap and lots of clients do not read two-dimensional drawing at all. Period. They might say they understand but in fact they are not…

> … many people will look at you right in your eyes and say: "Oh yeah I understand the plans." And they just simply don't have the experience to really understand the drawings…

> The architects tend to think everybody understands the drawings but the client really doesn't…

Sometimes the combined efforts of digital and physical models can cause troubles for clients trying to fully understand a design, especially with regards to the interior spaces. Therefore, architects have to seek out other ways to help them. The aforementioned full-sized mockups have been effective, but are impractical in most circumstances; thus, other media must be implemented. Among these forms of media, rendered animations are increasing in use. They have recently gained a wider level of popularity because good quality animation is pleasant to watch and can help clients better understand a design. Architect B notes:

> … in fact the very first time we actually did an animation was because… that client cannot envision what that space would be inside. They saw the physical model, they saw digital renderings… They could see it… but they could never understand what it felt like. That was the first time I said we've got to do an animation. It was not primitive, it was pretty well done and it went into the building, went through it, went up the escalator… so they finally got it.

4.5 The Art of Marketing

> You look at all the ugly buildings around. It's certainly not just about architecture. It's about marketing. (Architect D)

Although the focus of the interviews was on architectural models, some architects took a step back and discussed the business and human relations side of design practice. Here the architects did not mean to downplay the importance of design, but rather wanted to emphasize the notion that a successful business required not only design and presentation skills but, more importantly, a good overall image: confidence, honesty, faithfulness, a good relationship with the clients, and also a client's trust in the architect's ability. After all, it is a business dealing with human beings, and according to Architect D, "You could be the best designer in the world but be the worst salesman."

All that means is that the choice of presentation media is only a part of the entire project. There were many other aspects contributing to good practice, and a quality design was not enough to secure a successful practice. Architect D stated:

> … I think it's about you, yourself talking, the person… Your passion, your enthusiasm, your vision... To me, the thing comes out of your mouth that convinces me is more important than anything.

4.6 Model Making and the Design State of Mind

The making of physical models was not only considered to benefit the communication and design process, but more than that, it also showed a firm's commitment to the ideology of the architectural practice, according to some architects. Architect C noted:

> … because the designers find that's a good way to work, and probably, it's an example of the difference between firms where design is keen and "Design" with a capital D, as opposed to firms that are interested in the business of architecture and producing work and so on…

There were some "Starchitects" who were dedicated to model making and regularly employed professionals to build their physical models. However, Architect C observed that the majority of design firms didn't have resources to spare for such intensive building and use of physical models, and:

> … if you look at their office, they build hundreds of models for the same project, they will build 40 models for one study at one scale, and when they go to another scale they build 40 more models, to study other aspects…

> …while we were working with them, they proudly took us to their model shop. The shop was huge; it has all kinds of technology and equipment to help them to make models and they had three or four people who were employed to do nothing but build models. These are not architectural students, these are model builders. Their whole career path was to be constantly building models for the designers who were testing different things…

> It's not common… well it's not uncommon that any architect will tell you "ah yes, we can do models." But not all of them will devote that kind of resources and personnel to build their models.

One interviewee suggested that some firms are more technically-oriented while some are more interested in the expression of form. Architect C observed that one could calibrate a firm's passion by looking at the type of models they make:

> …I believe model building, if it's a passion of a firm, you can tell what their interest is by observing what kinds of models they focus on, so the ones who look at the technical stuff would probably well-regarded for their technical expertise, the ones build enough for the different models to show how the mullions on the high-rise building will look like are much more interested in a way the building looks...

So how did this devotion to model making contribute to the ideology of the design practice? Did such design state of mind correlate to those firms that were recognized as being closer to the pinnacle of the industry? Some of the architects interviewed believe that an emphasis on models could serve as a firm's statement of commitment, and enhance their design quality in certain aspects. According to Architect C:

> … some firms are more interested in [the] economics of the practice and just to simply get the work out of the door, they are not focusing on… it's hard to say that they are not interested in quality… But they don't have the same level of attention to either the technical quality or their design

quality, the aesthetic quality if you will, as the firms that emphasize the model building.

CHAPTER V

QUANTITATIVE METHODOLOGY

This chapter presents the quantitative results of this study, including the detailed procedures for the stimuli design and construction, experiment design, and subject recruitment. It also presents a pilot study that was conducted to reveal potential problems, and the revisions performed for the final experiment. An analysis of the results is presented in Chapter 6.

5.1 Research Design Overview

This part of the study adopted a gaming exercise for students. Sanoff (1979) pointed out that games can help people understand complex environmental forces. Therefore, in this research context gaming serves as a valid evaluation method for understanding the environment.

Simple geometric shapes have been used by many researchers in studies related to spatial abilities; the ability to rotate objects was one of the primary advantages of VE in helping people understand three dimensional objects (e.g., Baki et al.; Meijer & van den Broek, 2010; Schnabel & Kvan, 2003). Unlike the abstract geometries used in many other studies, in this study I designed a series of cube-based simple geometries that resemble parts of buildings or individual buildings. They could be combined to form more complex shapes, like larger buildings or building complexes. Schematic fenestration was also added to certain faces of the geometries to simulate a more realistic built environment than simple abstract forms.

The stimuli for this project consisted of two types of models, one physical and the other digital. Participants were asked to perform a series of tasks, and their performance was evaluated according to a predetermined set of criteria. Questionnaires were also given to participants to help researchers further evaluate participants' exercises.

5.2 Stimuli Design

Two types of models were included in this study; these models were located within the context of two particular types of stimuli. The first type was a modern, single-family residence, and the second was a high rise office complex. Each type had two designs with two different geometries; each design also had two identical models – a computer generated digital model and a 3-D physical model - so that there were a total of four designs and eight models. The detail levels between the digital and physical models were kept the same.

Two sets of blocks were designed to be the basic components of these models. In each set, there were ten different blocks; each block's geometry was unique. One of the single family residences and one of the office complexes could each be constructed using one set of blocks; the other block set could be used to construct the other two designs.

The geometry of the blocks was based on a 10' x 10' x 10' cubic module as the starting unit, with a scale of 1" = 8' - 0" for the house model. When constructed as an office model, each cubic module was assigned a dimension of 20' x 20' x 20', so the scale became 1” = 16’ – 0”. The scales of choice were some of the most commonly used scales in architectural design practice.

Addition, subtraction, and rotation were all applied based on a set of rules referred to as the principle of shape grammar (Stiny, 2006). The purpose of these designs was to develop a valid and replicable tool for future studies so that the results could be vertically and horizontally compared. The basic requirement was that each block had a unique geometry; there were 20 different blocks in the two sets. The rules for geometry generation are further explained below.

SET 1

I started with two 10’ × 10’ × 10’ cubes as the base block (Figure 5.1):

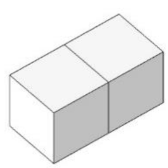

Figure 5.1 Two Cubes

With each turn, I added two more cubes to the base block, until there were four different blocks (Figure 5.2):

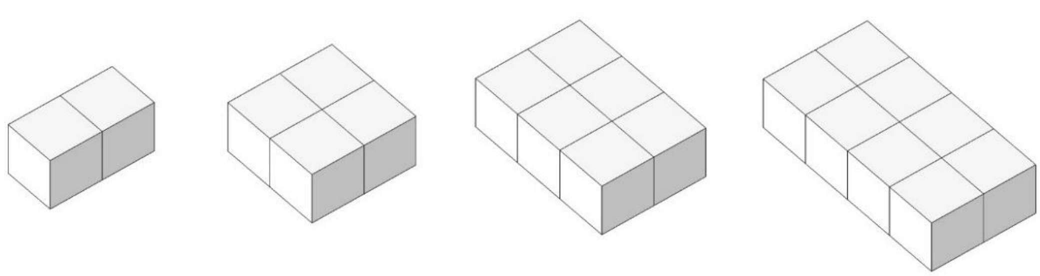

Table 5.2 Four Blocks

I then subtracted one cube from each block, except for the first one because it was already the smallest in this set (Figure 5.3):

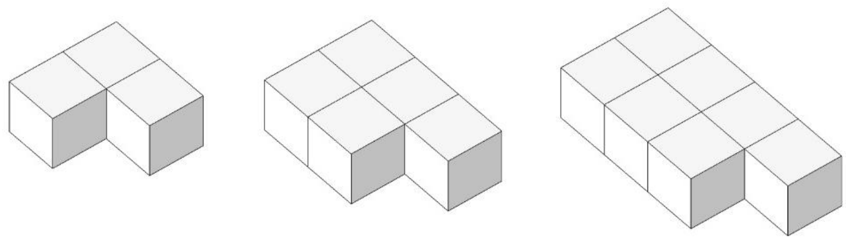

Table 5.3 First Subtraction

I further subtracted one cube from each block in the last step, except for the first one (Figure 5.4):

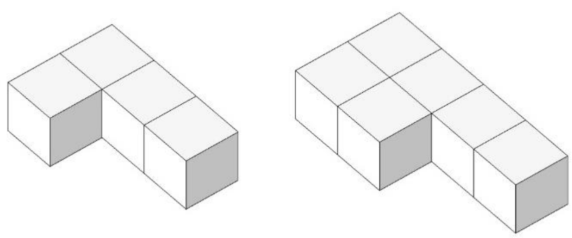

Figure 5.4 Second Subtraction

I then subtracted one cube. This time the rule only applied to the last block from the last step (Figure 5.5):

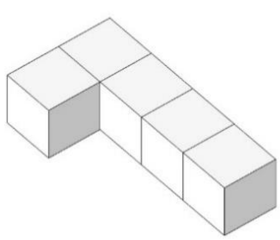

Figure 5.5 Third Subtraction

Eventually, a total of 10 blocks in Set 1 appeared as follows (Figure 5.6):

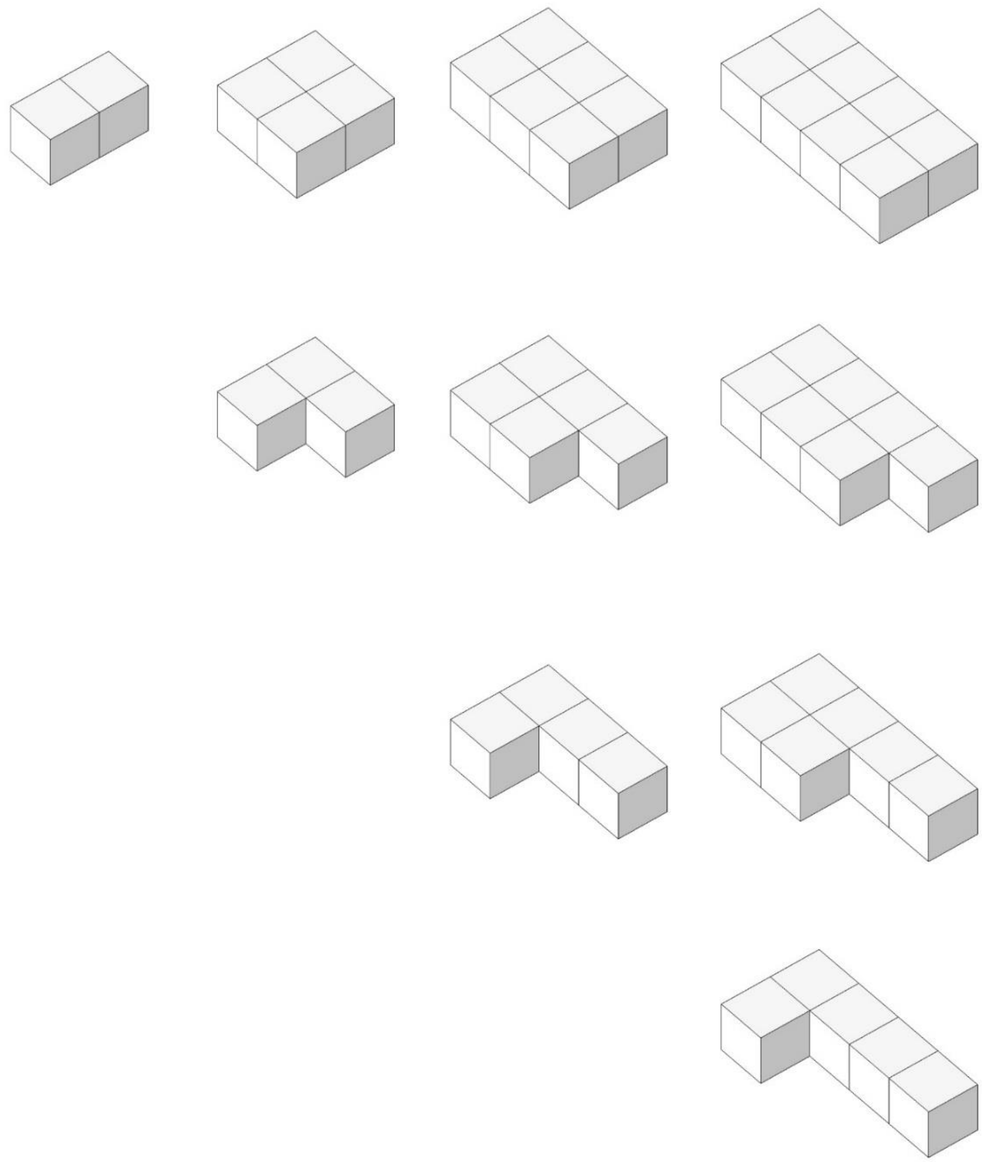

Figure 5.6 Set 1

SET 2

The second set needed to be completely different from the first set. One ground rule I followed was avoiding any geometry that has been used in block Set 1.

Since the 2-cube combination was used as the basic block in Set 1, Set 2 began with a 3-cube combination (Figure 5.7):

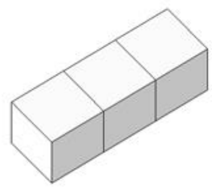

Figure 5.7 Three-cube Combination

I added one cube (Figure 5.8):

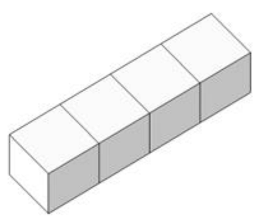

Figure 5.8 Add One Cube

Then I took one square at the end and began to rotate it around the rest of the geometry (Figure 5.9):

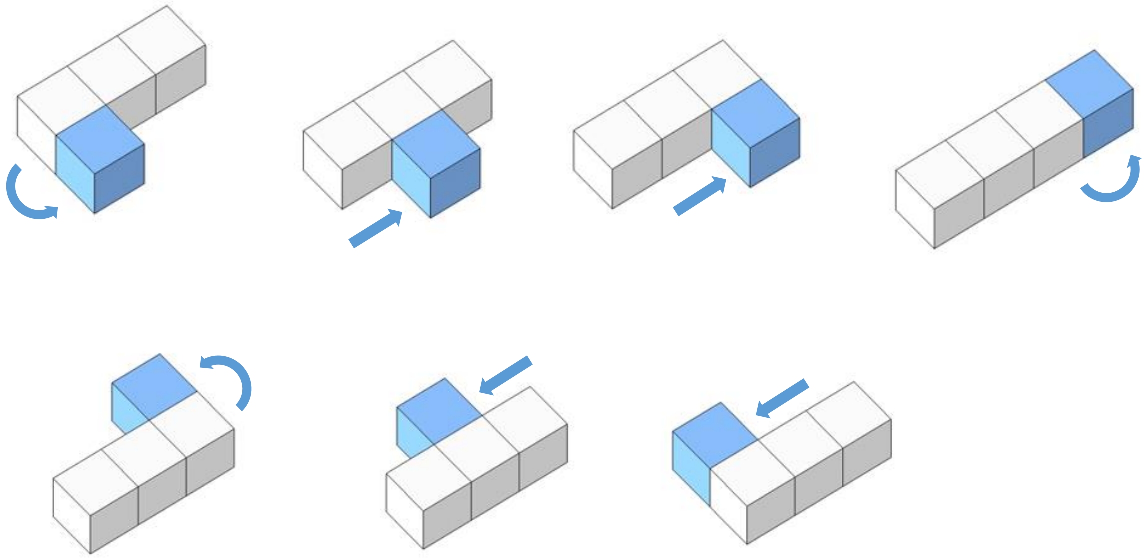

Figure 5.9 First Rotation

Since some of the geometries were either identical to or a mirror image of another geometry from Set 1 or Set 2, these duplicate blocks were deleted, leaving only the following (Figure 5.10):

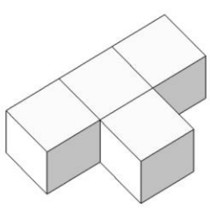

Figure 5.10 The Resulting Geometry

When I took two or three squares and rotated them, no new geometries were generated.

Then, based on the 4-square geometry, I took two squares at both ends and began to rotate them simultaneously, counter-clockwise, around the rest of the geometry. The result was as follows (Figure 5.11):

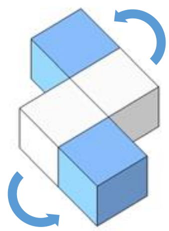

Figure 5.11 The Second Resulting Geometry

At this point, all of the geometries based on four cubes were generated. I then added one more cube, so that I could begin with five (Figure 5.12):

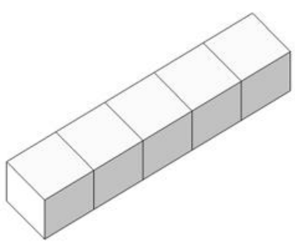

Figure 5.12 Five-cube Combination

Then I took one square at the end and rotated it, but avoided those shapes that already existed. Below is the only resulting geometry (Figure 5.13):

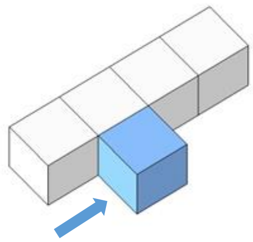

Figure 5.13 The Third Resulting Geometry

I next took two squares at one end and rotated them; two more geometries were created based on this rule (Figure 5.14):

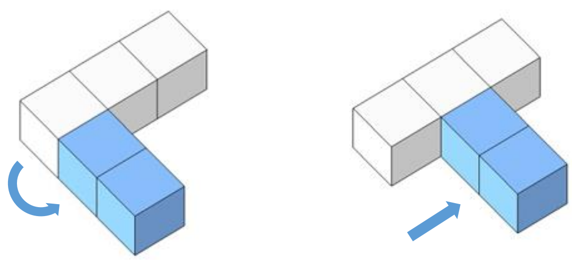

Figure 5.14 Two More Geometries

If I took three or four squares and rotated them, no new geometries were generated.

Lastly, I took two squares at both ends and simultaneously rotated them around the rest of the geometry in a counterclockwise direction. The resulting geometries were as follows (Figure 5.15):

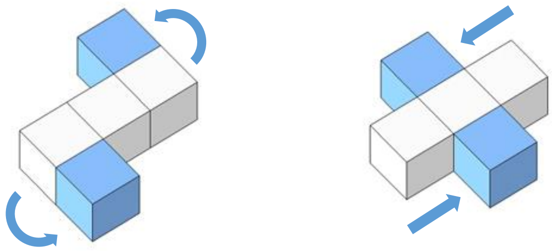

Figure 5.15 The Last Two Geometries

Now Set 2 had 10 geometries that differed completely from Set 1 (Fgure 5.16):

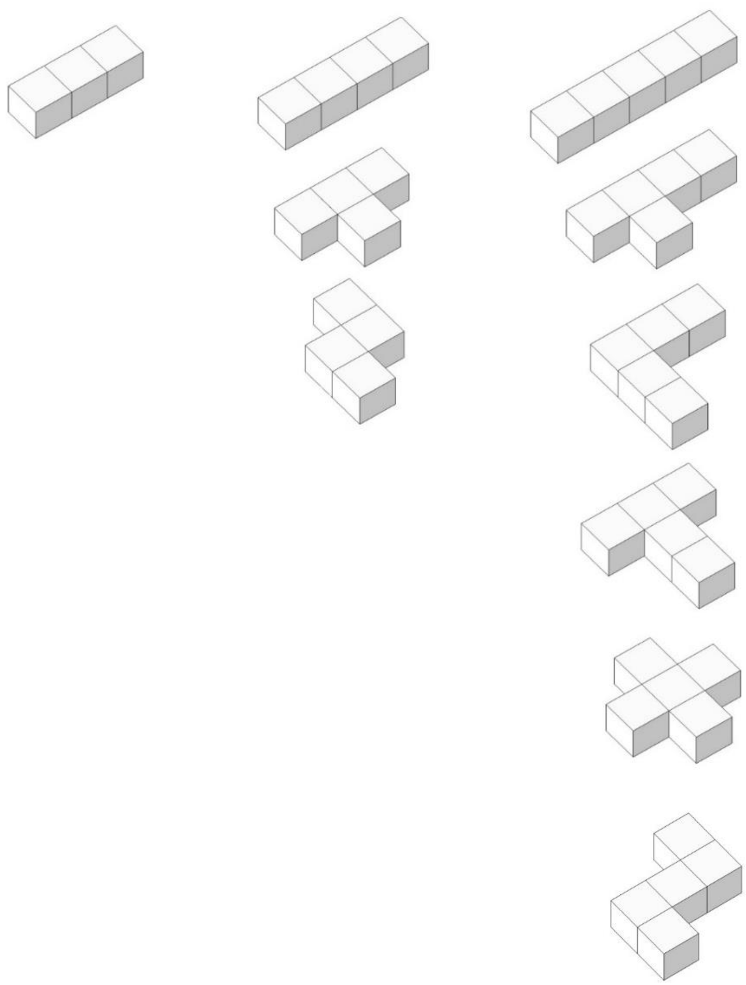

Figure 5.16 Set 2

Finally, a total of 20 geometries were generated for Sets 1 and 2.

Then, individual cubes in each geometry were “welded” together, and openings were added to certain façades. The final design of the blocks was then completed.

BLOCK SET 1 (Figure 5.17):

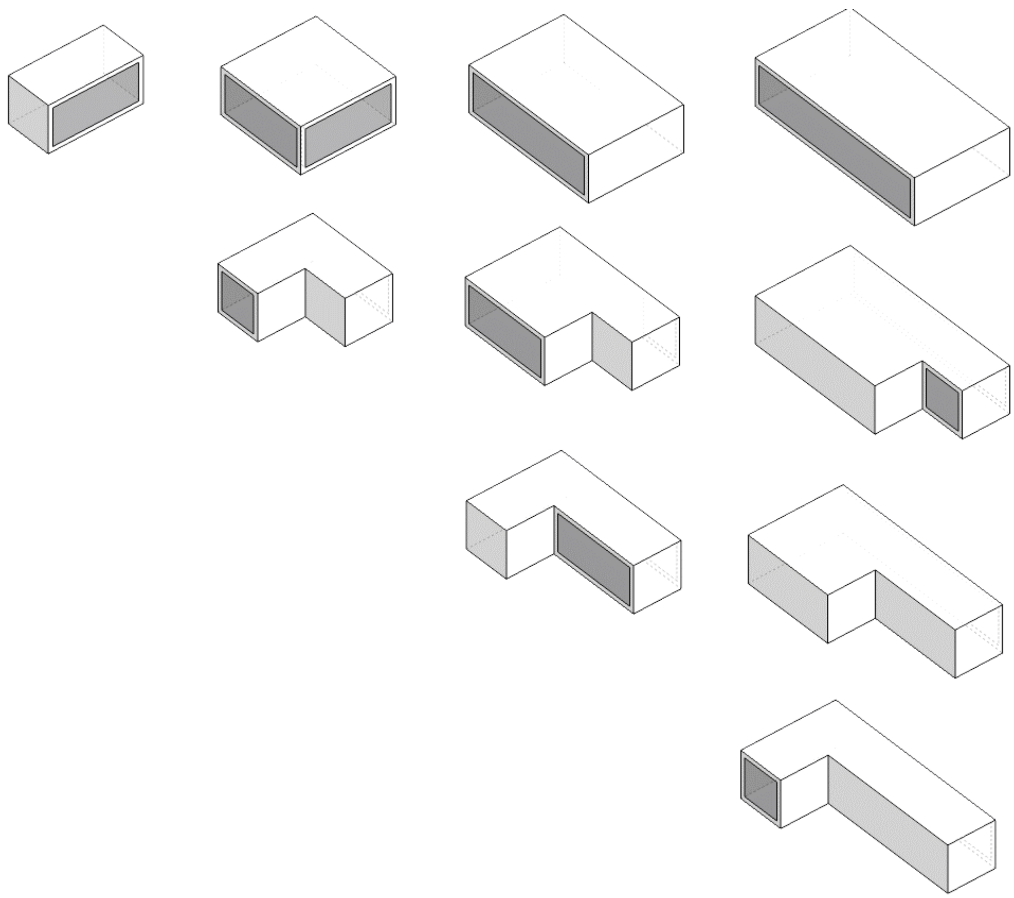

Figure 5.17 Final Blocks of Set 1

BLOCK SET 2 (Figure 5.18):

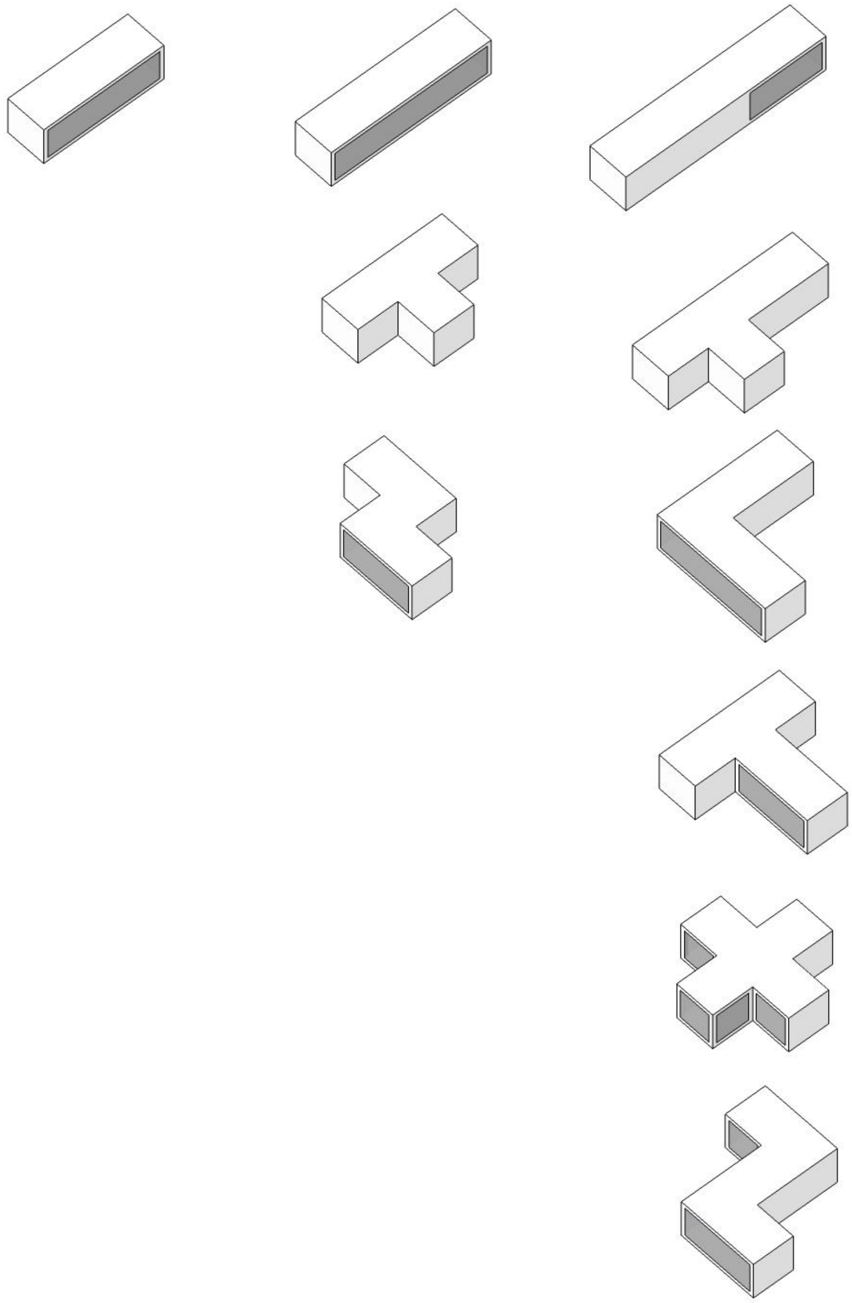

Figure 5.18 Final Blocks of Set 2

Blocks from each set were then combined to generate different conceptual designs. For the gaming exercise, each set was used to create two types of buildings: a modern, single family residence located at the corner of a crossroad, and an urban highrise office complex occupying four city blocks. Upon finishing the design, I began to build the digital and physical models.

Digital Models: Trimble® SketchUp® was the software program used to construct the digital models. This software program was chosen because it is widely used by architects displaying interactive models to their clients; it is favored due to its instant and rapid rendering capabilities. At the time of this research, the graphic quality and navigation smoothness of the interactive model presented by SketchUp was superior to models provided by other commonly used design software products such as AutoCAD, 3DsMax, Rhino, or Revit. The level of detail in the digital models was limited to the building exteriors. Each block was built as a sigle component and white was used as the primary color, with fenestrations represented by a white, transluscent material. The building sites were also included, but the detail was kept to a minimal level, with only basic illustrations of the streets and driveway. The color of the streets was light brown to match the effect of of a laser engraving on the physical model bases.

Physical Models: Researchers have used various materials to construct physical models, ranging from the exact materials used for the actual building (such as wood and plastic) (Seaton & Collins, 1972), to LEGO® blocks (Foreman & Stanton, 2003). In this experiment, the main material used for the physical models was 1/8” plywood. Each piece was precision cut by laser cutter and glued together by hand. The blocks were then sanded, primed, and painted white with a matte finish spray paint. The fenestrations were represented using a 1/16” frosted plastic sheet. The bases of the models were constructed from white matte boards, and the streets were engraved on the boards using a laser cutter. Six layers of matte boards were used to increase the thickness of the model bases.

The completed digital and physical models are shown below (see Figure 5.19).

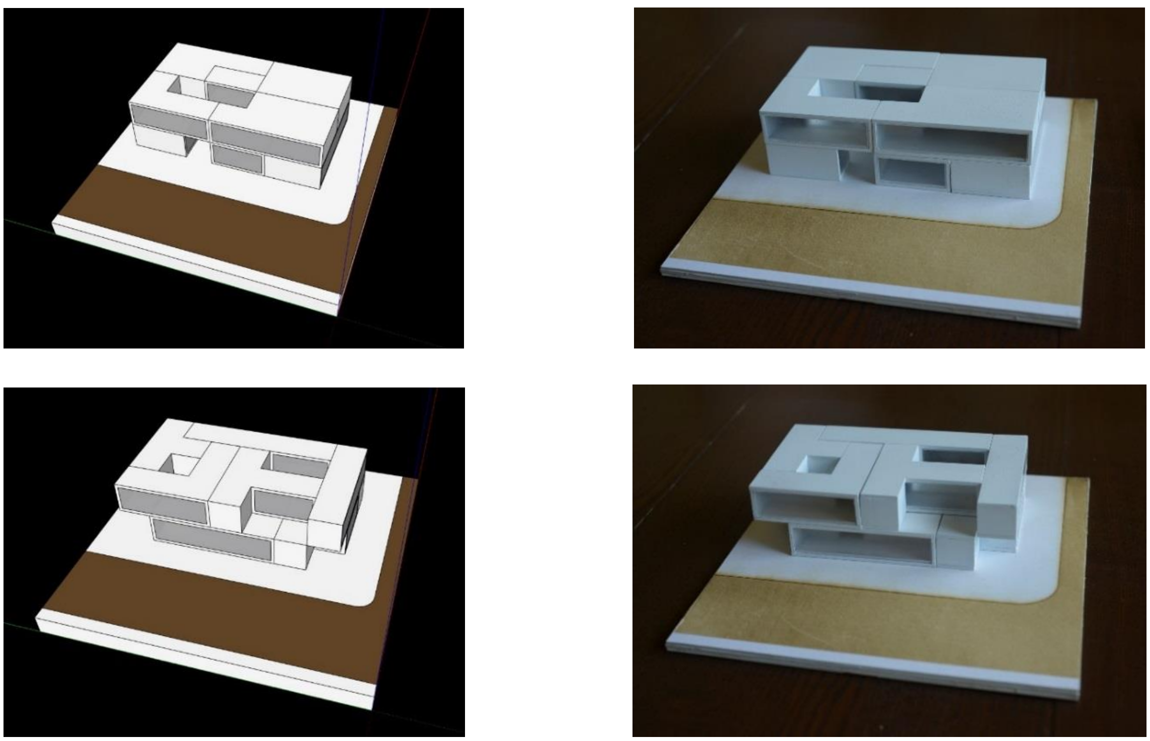

Figure 5.19 Digital Models and Physical Models

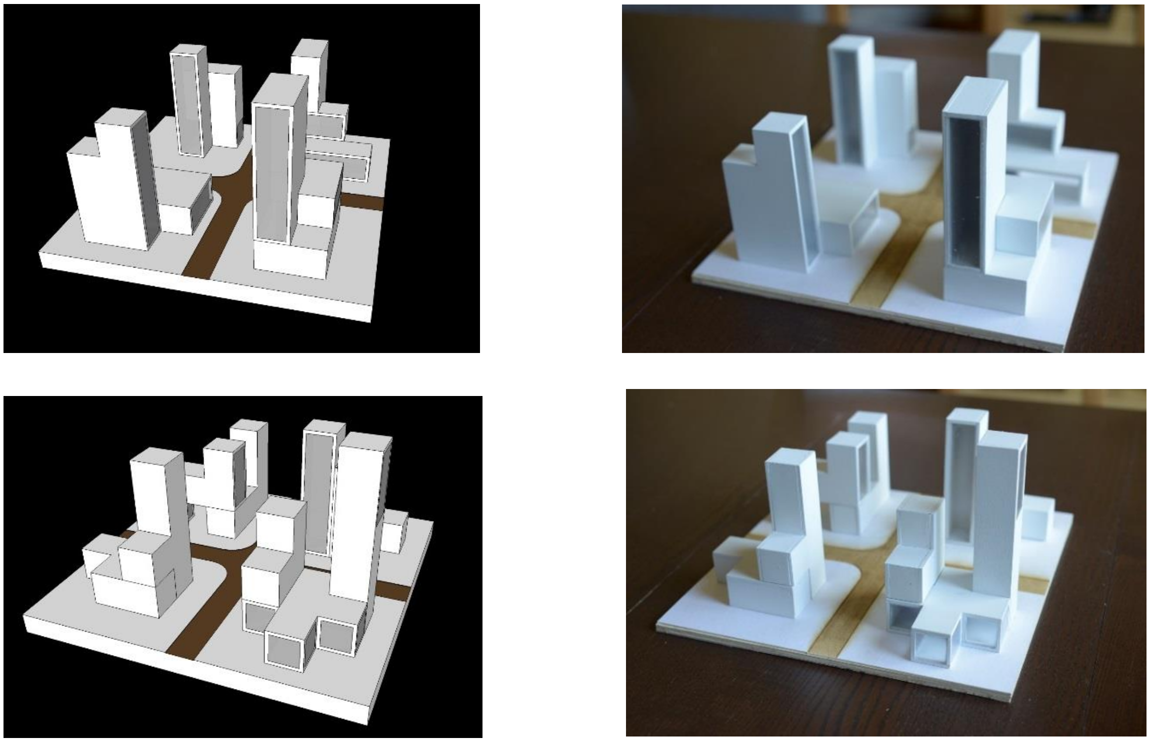

Figure 5.19 Continued.

5.3 Subject Recruitment

As discussed in Chapter II, architects and non-architects differ in their assessments of natural and built environments. The goal of this research was to study the general public's understanding of models; as a result, people who were trained in architectural design were excluded from the gaming exercise.

Subjects for the gaming exercise were recruited from an ENDS 101 class entitled Design Process, offered by the College of Architecture in the Spring 2014 semester. The class consisted of 175 undergraduate students from various academic disciplines.

A five minute class briefing asking for voluntary participation was given to the entire class. Before the briefing, I printed out the informed consent forms, which were handed out to everyone present. The briefing included a short speech accompanied by a series of PowerPoint slides describing the background and purpose of this research study. A signup sheet was then passed around the class, and students who were interested were able to choose their preferred time slots for the study.

5.4 Process

To describe the eight different models in an effective and succinct way, they were codenamed as follows: Digital House 1 (DH1); Physical House 1 (PH1); Digital House 2 (DH2); Physical House 2 (PH2); Digital Office 1 (DO1); Physical Office 1 (PO1); Digital Office 2 (DO2); and Physical Office 2 (PO2).

Each participant was asked to work on two different consecutive models, diverse in design and presented in different media, in order to minimize any carryover effect. For example, acceptable combinations included DH2 then PH1, or PO2 then DH1. Meanwhile, eight combinations - PH1 then DH1, PH2 then DH2, PO1 then DO1, PO2 then DO2 and each in their reverse, were excluded. The same block sets were used in both models, so a participant could have become familiar with them and yielded better (but inaccurate) results in their second task.

Based on this principle, the total number of possible combinations from these eight models was 24 (Figure 5.20).

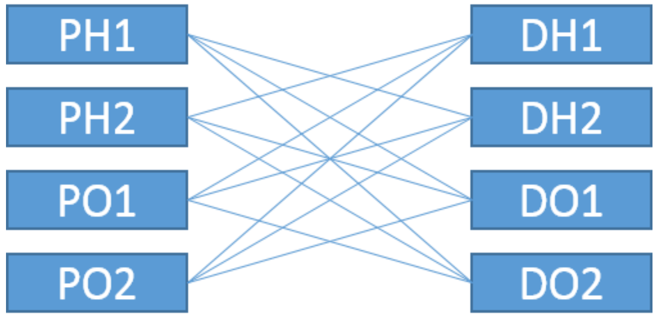

Figure 5.20 All Possible Combinations for Gaming Tasks

Three people were randomly assigned to work on each combination, so there were a total number of 72 participants in 24 groups. A detailed task assignment is illustrated in table 5.1 in the next page.

The gaming task for each individual took about 25 minutes. There were two sessions for each participant, each session consisted of two stages, and each stage took five minutes. The first part was the “Learning” stage. Participants were asked to study either a computer generated model displayed on a monitor, or a physical model that has been constructed by myself beforehand. For those who started with the digital models, a brief instruction regarding rotating, zooming and panning the virtual camera was given. They were allowed to look at the model from any angle they desire and zoom in/out freely. For those who studied the physical models, they can also look at the models from any angle by holding the base to spin it freely. Just like the digital models, the participant was not allowed to disassemble the wooden blocks while studying the models.

Table 5.1 Gaming Task Assignment

	FIRST MODEL	SECOND MODEL
GROUP 1	*PH1*	*DH2*
GROUP 2	*PH1*	*DO1*
GROUP 3	*PH1*	*DO2*
GROUP 4	*PH2*	*DH1*
GROUP 5	*PH2*	*DO1*
GROUP 6	*PH2*	*DO2*
GROUP 7	*PO1*	*DH1*
GROUP 8	*PO1*	*DH2*
GROUP 9	*PO1*	*DO2*
GROUP 10	*PO2*	*DH1*
GROUP 11	*PO2*	*DH2*
GROUP 12	*PO2*	*DO1*
GROUP 13	*DH1*	*PH2*
GROUP 14	*DH1*	*PO1*
GROUP 15	*DH1*	*PO2*
GROUP 16	*DH2*	*PH1*
GROUP 17	*DH2*	*PO1*
GROUP 18	*DH2*	*PO2*
GROUP 19	*DO1*	*PH1*
GROUP 20	*DO1*	*PH2*
GROUP 21	*DO1*	*PO2*
GROUP 22	*DO2*	*PH1*
GROUP 23	*DO2*	*PH2*
GROUP 24	*DO2*	*PO1*

The second part of the gaming exercise was the “Constructing” stage. Participants were asked to reassemble the models based on their memory. For those who studied the computer models, I presented the wooden blocks on the desk in a randomly arranged array. For those who studied the physical models, I quickly disassembled the models, shuffled the blocks and arranged them in a random fashion. The corresponding model bases were also provided before the stage began. This two-part process was based on the research study designed by Schnabel & Kvan (2003), who have used a similar two-stage process: study and memorize – reconstruct based on memory in their research project to investigate people’s level of understanding of the geometry presented with different kinds of media.

After each session, the participant was asked to fill out a simple questionnaire asking about their experience. The questions were regarding:

- The pleasantness of the study model;
- How easily can one manipulate the study model;
- The difficulty level of this particular gaming task.

To further match the appearance between the digital and physical models, all gaming tasks were conducted indoors under ambient fluorescent lighting condition to avoid strong cast shadows. The shadow display in the computer software was also turned off.

5.5 Evaluation Criteria

5.5.1 Overview

Upon finishing each session of the gaming task, I recorded the final results by taking a series of photographs. For each model, five photographs were taken. Four of them were taken from four directions of the model, and the fifth photograph was taken from the top of the model. For the house models, I removed the level two assembly and set it aside before taking the top shot so it was easier to see the assembly on level one.

To quantify the results, three criteria were used to evaluate the models constructed by the participants. Each block was assessed individually and the number of successfully constructed blocks among all blocks in a model based on each criterion was calculated towards the final score and marked as percentage. The details of each criterion are further explained below.

5.5.2 Criterion 1: General Location

For the house models, general location criterion evaluated whether a block was on the correct floor. Any block that was on the correct floor received one score. The exact location or orientation of the block was ignored. Since there were ten blocks in each model, the final results were converted to percentages by dividing 10. As illustrated in Figure 5.21 below, the left image showed the correct layout of level one of house 1, the right image was a re-constructed model by one of the participants. The highlighted pieces all qualify one score in this criterion, the resulting score on this level was 4/10 = 0.4. The same principle applied to level two and the percentages on both levels were added to yield the final score.

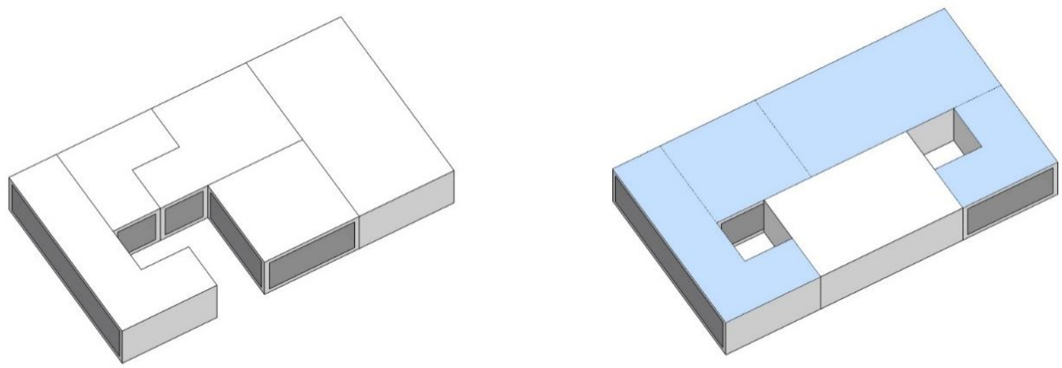

Figure 5.21 General Location Evaluation Sample: House

For the office complex models, the general location criterion evaluated whether a block was in the correct city block. Any block that was in the correct city block received one score regardless of its exact location or orientation. An example of the application was illustrated below (Figure 5.22). The left image was the correct arrangement for two city blocks in office model 2, each of those highlighted pieces in the right image qualified 1 score, and the final score for this part of the model was 3/10 = 0.3.

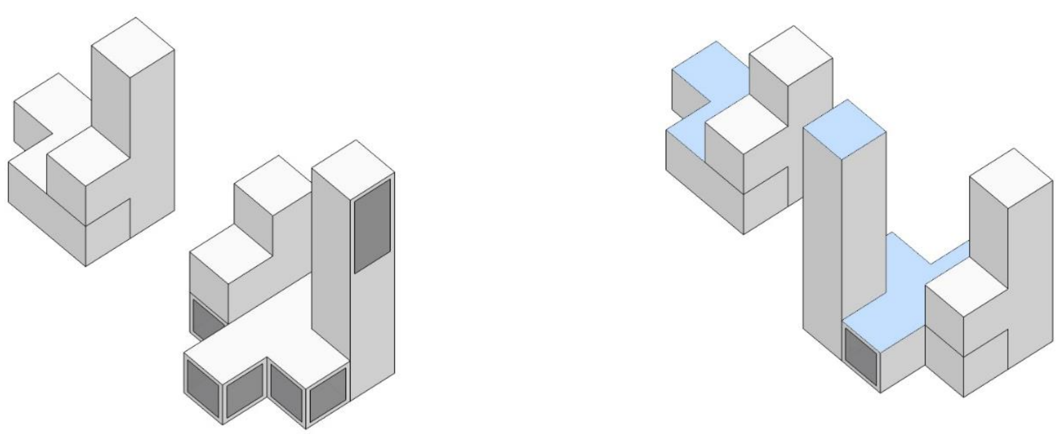

Figure 5.22 General Location Evaluation Sample: Office

5.5.3 Criterion 2: Adjacency

The adjacency criterion evaluated the appropriate relationship between two directly adjacent blocks. The total number of this relationship in each model was calculated by counting how many one-to-one adjacencies were present regardless of their orientation. This number varied in each design, and the final score was presented by percentages. An example was illustrated below in Figure 5.23. Each blue arrow indicated a relationship worthy of 1 score.

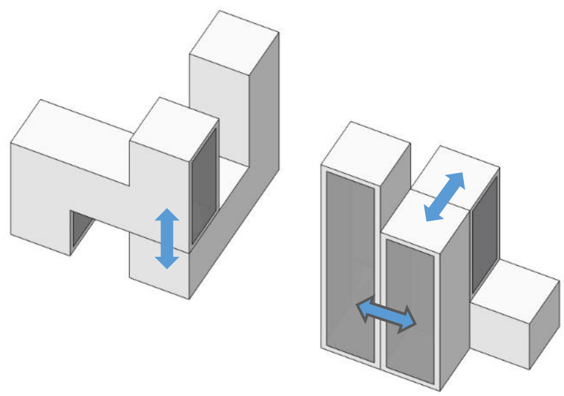

Figure 5.23 Adjacency Evaluation Sample: Office

The same principle also applied to the house models. An evaluation example is presented below in Figure 5.24. The left image is the correct arrangement with blue arrows indicating all the one-to-one adjacencies, in this case the number was 6. The image to the right was a model constructed by one of the participants. Each arrow indicated the correct relationships that would receive 1 score, and the final score was 3.

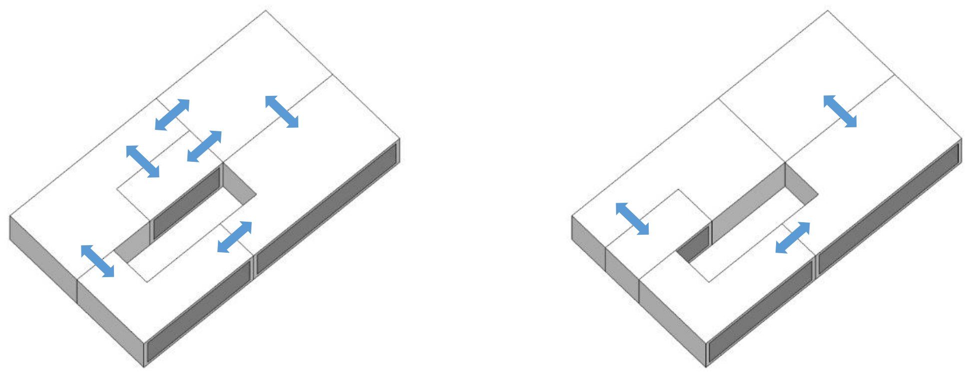

Figure 5.24 Adjacency Evaluation Sample: House

5.5.4 Criterion 3: Exact Location

The third criterion was straightforward. It evaluated whether a block was at exactly the same location as the original design, including its orientation. An example was illustrated in the Figure 5.25 below. The image to the left was the correct layout of office 1. The image to the right was the result from one of the participants. The highlighted pieces fulfilled the Exact Location criterion and received a total score of 5.

5.6 Pilot Study

5.6.1 Overview

The purpose of the pilot study was to evaluate the appropriate timing for the gaming practice, and other issues regarding feasibility or unfavorable events that may occur before launching the study (Hully, 2007). It may also reveal problems in the models and the questionnaire.

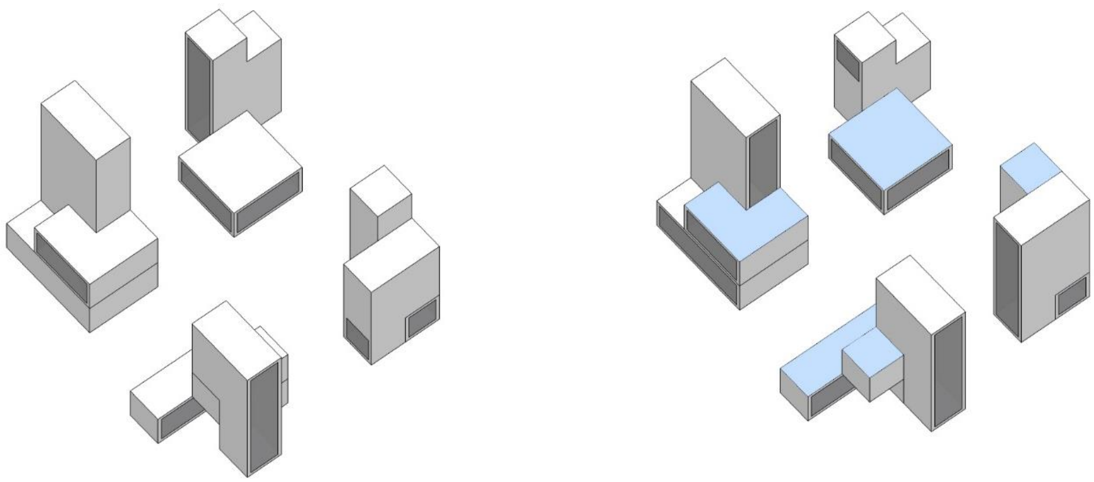

Figure 5.25 Exact Location Evaluation Sample: Office

A total of six people participated in the pilot study, they were chosen amongst my personal acquaintances that were not trained in architecture major.

5.6.2 Process

The procedure of the pilot studies followed the designated methodology described in the previous chapter: Each participant was given two models to study consecutively. Five minutes were allowed to study each model, and another 5 minutes were given to use the wooden blocks to construct the models based on their memory. Upon finishing each model, I asked each person to fill out the questionnaire regarding the study model he or she have seen, and the experience of the finished gaming task.

The pilot studies were conducted in two different locations, both with a large table as the working surface and ambient indoor lighting condition. A wristwatch countdown timer was used to precisely control the amount of time. During the entire process I was sitting 5-6 feet away observing the participants doing their tasks.

5.6.3 Results and Observations

In summary, the pilot study process went smoothly with no undesired event that suggested the need for major revision of the study design or instruments. However, there were some interesting findings based on observing participants' actions that called for small adjustments in the final experiments.

Generally, many participants started to show signs of confidence after only 2-3 minutes' study time of the models and becoming less attentive and patient. They did not, in fact, memorize the model components to the level of their confidence, which was reflected by their results.

Another observation was that while constructing the models, participants usually finished the majority of their memorized parts in a relatively short amount of time, and then tried to fit in those less familiar pieces. If the final geometry could not be achieved, or there were pieces left that could not be fitted into the final models, they tended to tear down the finished pieces and start over for the purpose of achieving a complete model with every piece included. That was the moment they shifted their tasks from "memorizing" to "creating".

Since almost no one could correctly memorize all the parts of a model, the time up notice caused a little anxiety among the participants. Many participants requested extra time to fit each scattered wooden block into the final model.

5.6.4 Discussion and Adjustments for Final Experiments

Several adjustment decisions were made based on these observations.

The amount of time to study the models could be reduced to four minutes. The time for constructing the models is also reduced to four minutes, in order to prevent participants from creating their own versions.

In order to keep the amount of time for constructing the models consistent and avoid people from panicking, each participant will be notified in the beginning that extra time is not allowed. Also, notifications will be given to each participant when there was 1 minute left so he or she can keep track of time.

CHAPTER VI

QUANTITATIVE RESULTS: GAMING AND QUESTIONNAIRES

This chapter summarizes the analysis of the data that were gathered through gaming tasks given to test subjects. Three analyses are presented in this chapter: The first summarizes participants' questionnaire answers, the second compares gaming task Results Based on the evaluation criteria described in the previous chapter, and the last examines the relationship between participants' questionnaire answers and their task results. Different statistical methods were utilized to conduct these analyses which in turn were explained in detail.

6.1 Overview

The quantitative portion of this research study gathered three types of data: gaming task performance, questionnaire results, gender and academic major information. The first was the results from subjects' gaming tasks. The method has been described in detail in Chapter 3, but is briefly summarized here. A participant studied and memorized a model presented either in digital form or physical form, and then were asked to put the model pieces back together within a given period of time. Then the task repeated once more with a different model. The final models constructed were documented with a camera and evaluated based on a set of criteria. The criteria included: General Location - which judged whether a block is in the correct floor for the house model, or city block for the office complex model. Adjacency – which judged whether two adjacent blocks were in the correct relationship; and Exact Location – which judged whether a block was in its exact location, including the orientation of the window openings.

The second type of data was derived from the questionnaire answers after participants finished each gaming task. The survey addressed three issues: the pleasantness of the study model; the ease of manipulation while studying the models, and the overall difficulty of the gaming task. The associated questions were presented in the form of a seven point Likert scale. In addition to gaming results and the three questions in the survey, gender and field of study information was also gathered.

The quantitative data analysis was conducted in three phases. The first phase of analysis addressed the differences in participants' gaming task results that were categorized by different types of media, and different types of building models. This phase aimed at revealing how different representation media affect people's spatial understanding, and whether differences in building types affected people's spatial understanding. The second phase of analysis focused on the questionnaires, which addressed participants' evaluation and experience towards different types of media and building models. The third phase identified and defined any relationship that might exist between the gaming task results and participants' evaluation, as well as the relationships between questions, for example, pleasantness and level of task difficulty.

In the first two phases, Wilcoxon Rank-Sum tests were used to accomplish the comparison studies between the variables. Descriptive statistics were also used to describe basic characteristics of the data. The third phase adopted Spearman's rank-order correlation which helped to determine monotonic relationships between variables.

6.2 Analysis Methods

JMP 10 software package was chosen to conduct the statistical analysis. Output from the software product include tables, and two- and three- dimensional graphs**.** All data from the gaming tasks were organized and coded in Microsoft Excel before importing into the JMP software interface and a series of statistical analysis were conducted. Data organization, and statistical analysis methods are further explained below.

6.2.1 Data Organization

6.2.1.1 Data Sheets for Wilcoxon Rank-Sum Tests

To analyze the difference between physical house models and digital house models, all PH1 and PH2 rows were reassigned a new codename "PH", similarly, all DH1 and DH2 rows were reassigned a new codename "DH". For this particular analysis, all other data entries were deleted. The same principle was applied on other raw data sheets that aimed at comparing:

- Physical office models (PO) and digital office models (DO),
- Digital house models (DH) and digital office models (DO),
- Physical house models (PH) and Physical office models (PO).

To compare the overall digital models and physical models, all DH1, DH2, DO1 and DO2 rows were reassigned as "Digital", and all PH1, PH2, PO1 and PO2 rows were reassigned as "Physical". Similarly, to compare the overall house model and office models, all DH1, DH2, PH1 and PH2 rows were reassigned as "House" and all DO1, DO2, PO1 and PO2 rows were reassigned as "Office".

6.2.1.2 Data Sheets for Pearson's Correlation Analyses

The data organization for correlation analyses followed the similar principles as the sheets constructed for t-tests. Since multivariate method was chosen, the evaluation scores and questionnaire answers were vertically aligned in six columns and the rows were grouped based on the analyses to be conducted.

6.2.1.3 Data Arrangement

This study consisted two types of data – one from the evaluation scores of the gaming tasks and the other from questionnaire answers. Each participant worked on two different models, and for each model, there were three evaluation scores and three questionnaire answers. That meant each participant had a total number of $(3+3)\times2=12$ data entries. The total number of participants was 72, so the total number of data entries was $72\times12=864$.

Several ways of data organization were employed to suit different statistical analysis methods. To begin with, each participant's data was coded and vertically stacked. Each row presented all twelve data entries from one subject, arranged in the order of: questionnaire answers for the first task - gaming task evaluation scores for the first task – questionnaire answers for the second task – gaming task evaluation scores for the second task. Codenames for the models the participant worked on were also reflected in a new column added on the right end. An example of the organization is shown in table 6.1 below.

Table 6.1 Example of First Step Data Organization

SUBJECT	Q1	Q2	Q3	E1	E2	E3	TYPE		Q1	Q2	Q3	E1	E2	E3	TYPE
1	6	1	4	0.4	0.000	0.2	DH1		4	2	6	0.5	0.250	0.3	DO1

The next step was to separate the data based on different types of models each participant worked on, so each participant's data was split into two rows, and each column only consisted of six data entries. The data table now is vertically organized in the order of: PH1-PH2-DH1-DH2-PO1-PO2-DO1-DO2. An example of the organization is shown in table 6.2 below.

Table 6.2 Example of Second Step Data Organization

SUBJECT	Q1	Q2	Q3	E1	E2	E3	TYPE
1	6	1	4	0.4	0.000	0.2	DH1
2	6	3	6	0.5	0.050	0.2	DH1

This table served as the "raw data sheet" and was then copied into several new sheets to be further developed based on the designated statistical analysis methods.

6.2.1.4 Wilcoxon Rank-Sum Test

The gaming practice with blocks produced some non-normal distributions in participant task results, the scenarios are analyzed below:

- If a participant could only remember three out of 10 blocks, the chance for him or her to get any of the other seven pieces correct was extremely low.

- However, if a participant could remember seven out of 10 blocks, the chance for him or her to get any of the remaining three pieces correct was very high, due to reduced uncertainty.

Thus, those who could remember more blocks were more likely to finish more than they could remember. As a result, the data may be non-normally distributed.

Thus, the Wilcoxon Rank-Sum test, also known as the Mann-Whitney U test, was adopted to compare the treatments. As compared to the Student's T-test, the Wilcoxon Rank-Sum test is more suitable for non-normally distributed data, and its normal approximation is appropriate for relatively small sample sizes (Wilcoxon, 1945; Bellera et al., 2010).

6.2.1.5 Pearson's Correlation

Pearson's Product Moment Correlation was used between the variables in this study. The main purpose for choosing this method was to investigate how well participants' self-reporting related to the gaming task results, based on the newly developed evaluation criteria. A potential problem with the correlation is that it does not suggest a cause and effect relationship (Ott & Longnecker, 2001). However, the study did not aim to determine a causal relationship between the variables. All variables were included in a multi-variant test conducted by the JMP software program.

6.2.2 Description of Participants

Basic information regarding gender and field of study was gathered during each subject's participation.

6.2.2.1 Gender

Among the total number of 72 participants, 30 were female, which represented 41.67% of the sample population, and 42 were male, which was 58.33% of the sample population.

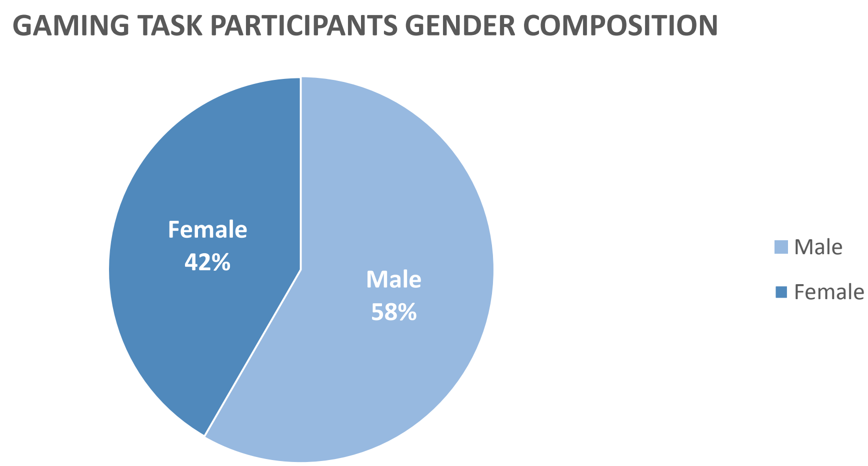

Figure 6.1 Gaming Task Participants Gender Composition

6.2.2.2 Academic Major

The breakdown of the academic majors of the participants is shown in the pie chart below. About 40% of the participants were from the College of Engineering, 25% from the College of Science, 17% from the College of Business, 14% from the College of Liberal Arts, 2% from the College of Education, 1% from the College of Geology, and 1% from General Studies.

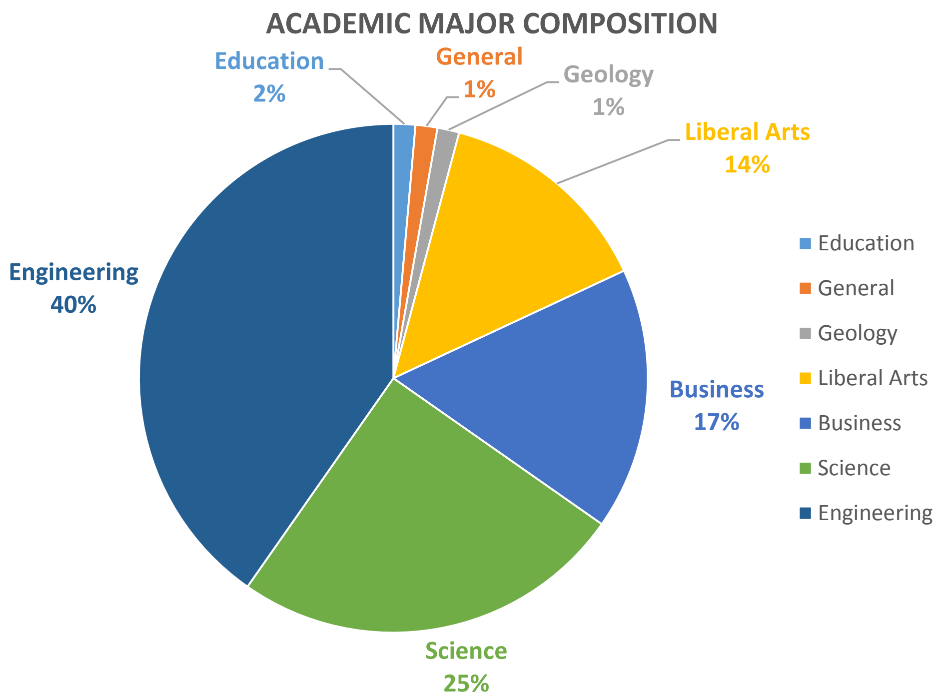

Figure 6.2 Academic Major Composition

6.3 Quantitative Results

The quantitative results section of this research includes three parts: the analysis of the questionnaire answers, the analysis of the gaming task results and a multivariate analysis. To reduce redundancy of the data, only significant results are presented in this section. The complete report of data analysis with each pair of comparison can be found in Appendix B.

6.3.1 Questionnaire Results

This section presents the statistical analysis of the questionnaire answers. Six levels of comparison were made: Digital houses versus physical houses, digital offices versus physical offices, digital houses versus digital offices, physical houses versus physical offices, overall digital versus physical, and overall houses versus offices.

6.3.1.1 Digital Houses Versus Digital Offices

Overall Difficulty: Easy – Difficult

Outcomes of the two seven-point Likert Scale questionnaire answers regarding the question – How easy do you think the gaming task is? - were compared using the Wilcoxon two-sample Rank-Sum test. There were n=36 entries in each test group to be compared, the total number of entries was n=72.

Table 6.3 Quantiles and Summary Statistics of Participants' Response of Q3.

	N	QUANTILES					MEAN	STD. DEV	UPPER 95%	LOWER 95%
		100%	75%	50%	25%	0%				
DH	36	7.00	6.00	5.00	4.00	1.00	4.78	1.35	5.24	4.32
DO	36	7.00	5.00	4.00	3.00	1.00	4.11	1.45	4.60	3.62

The medians of Q3 for Digital office and Physical office were 5 and 4, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The comparison result showed that the null hypothesis can be rejected, hence there was a significant difference between these two groups ($S=1137$, $Z=-2.04$, $p < 0.05$) (Table 6.3 and 6.4).

Table 6.4 Wilcoxon Non-Parametric Rank-Sum Test for Q3 Between Digital House and Digital Office Samples

S	Z	Prob > |Z|
1137.00	-2.04	0.04

6.3.1.2 Digital versus Physical

Overall Difficulty: Easy – Difficult

Outcomes of the two seven-point Likert Scale questionnaire answers regarding the question – How easy do you think the gaming task is? - were compared using the Wilcoxon two-sample Rank-Sum test. There were n=72 entries in each test group to be compared, the total number of entries was n=144.

Table 6.5 Quantiles and Summary Statistics of Participants' Response of Q3.

	N	QUANTILES					MEAN	STD. DEV	UPPER 95%	LOWER 95%
		100%	75%	50%	25%	0%				
DIGITAL	72	7.00	5.00	5.00	4.00	1.00	4.44	1.43	4.78	4.11
PHYSICAL	72	7.00	5.00	4.00	3.00	1.00	3.97	1.43	4.31	3.64

The medians of Q2 for Digital and Physical were 5 and 4, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The comparison result showed that the null hypothesis can be rejected, hence there was a significant difference between these two groups (S=4706, *Z*=-2.10, $p < 0.05$) (Table 6.5 and 6.6).

Table 6.6 Wilcoxon Non-Parametric Rank-Sum Test for Q3 Between Physical House and Physical Office Samples

S	Z	Prob > |Z|
4706.00	-2.10	0.04

6.3.1.3 Houses Versus Offices

Overall Difficulty: Easy – Difficult

Outcomes of the two seven-point Likert Scale questionnaire answers regarding the question – How easy do you think the gaming task is? - were compared using the Wilcoxon two-sample Rank-Sum test. There were n=72 entries in each test group to be compared, the total number of entries was n=144.

Table 6.7 Quantiles and Summary Statistics of Participants' Response of Q3.

	N	QUANTILES					MEAN	STD. DEV	UPPER 95%	LOWER 95%
		100%	75%	50%	25%	0%				
HOUSE	72	7.00	6.00	5.00	3.25	1.00	4.47	1.40	4.80	4.14
OFFICE	72	7.00	5.00	4.00	3.00	1.00	3.94	1.45	4.29	3.60

The medians of Q3 for House and Office were 5 and 4, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The comparison result showed that the null hypothesis can be rejected, hence there was a significant difference between these two groups (S=4693.5, Z=-2.15, $p < 0.05$) (Table 6.7 and 6.8).

Table 6.8 Wilcoxon Non-Parametric Rank-Sum Test for Q3 Between House and Office Samples

S	Z	Prob > |Z|
4693.50	-2.15	0.03

6.3.2 Gaming Task Results

6.3.2.1 Digital Houses Versus Physical Houses

General Location

The General Location (GL) criterion was used to compare the gaming task results between Digital House and Physical House reconstructions. There were n=36 entries in each test group to be compared, the total number of entries was n=72.

Table 6.9 Quantiles and Summary Statistics of Participants' Results Based on GL Criteria.

	N	QUANTILES					MEAN	STD. DEV	UPPER 95%	LOWER 95%
		100%	75%	50%	25%	0%				
DH	36	1.00	1.00	0.70	0.50	0.30	0.71	0.25	0.79	0.62
PH	36	1.00	1.00	1.00	0.725	0.20	0.88	0.19	0.94	0.81

The medians of GL for Digital House and Physical House were 0.7 and 1, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The comparison result showed that the null hypothesis can be rejected, hence there was a significant difference between these two groups ($S=1579$, $Z=3.11$, $p < 0.05$) (Table 6.9 and 6.10).

Table 6.10 Wilcoxon Non-Parametric Rank-Sum Test for GL Between Digital House and Physical House Samples

S	Z	Prob > |Z|
1579.00	3.11	<0.05

Adjacency

The Adjacency (AD) criterion was used to compare the gaming task results between Digital House and Physical House reconstructions. There were n=36 entries in each test group to be compared, the total number of entries was n=72.

Table 6.11 Quantiles and Summary Statistics of Participants' Results Based on AD Criteria.

	N	QUANTILES					MEAN	STD. DEV	UPPER 95%	LOWER 95%
		100%	75%	50%	25%	0%				
DH	36	1.00	0.35	0.11	0.00	0.00	0.23	0.31	0.34	0.13
PH	36	1.00	1.00	0.38	0.09	0.00	0.47	0.40	0.61	0.34

The medians of AD for Digital House and Physical House were 0.11 and 0.38, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The comparison result showed that the null hypothesis can be rejected, hence there was a significant difference between these two groups ($S=1580$, $Z=3.01$, $p < 0.05$) (Table 6.11 and 6.12).

Table 6.12 Wilcoxon Non-Parametric Rank-Sum Test for AD Between Digital House and Physical House Samples

S	Z	Prob > |Z|
1580.00	3.01	<0.01

Exact Location

The Exact Location (EL) criterion was used to compare the gaming task results between Digital House and Physical House reconstructions. There were n=36 entries in each test group to be compared, the total number of entries was n=72.

Table 6.13 Quantiles and Summary Statistics of Participants' Results Based on EL Criteria.

	N	QUANTILES					MEAN	STD. DEV	UPPER 95%	LOWER 95%
		100%	75%	50%	25%	0%				
DH	36	1.00	0.50	0.30	0.13	0.00	0.35	0.27	0.44	0.26
PH	36	1.00	0.80	0.55	0.20	0.00	0.52	0.32	0.63	0.41

The medians of EL for Digital House and Physical House were 0.3 and 0.55, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The comparison result showed that the null hypothesis can be rejected, hence there was a significant difference between these two groups ($S=1512$, $Z=2.24$, $p < 0.05$) (Table 6.13 and 6.14).

Table 6.14 Wilcoxon Non-Parametric Rank-Sum Test for EL Between Digital House and Physical House Samples

S	Z	Prob > |Z|
1512.00	2.24	0.03

6.3.2.2 Digital Offices versus Physical Offices

Adjacency

The Adjacency (AD) criterion was used to compare the gaming task results between Digital Office and Physical Office reconstructions. There were n=36 entries in each test group to be compared, the total number of entries was n=72.

Table 6.15 Quantiles and Summary Statistics of Participants' Results Based on AD Criteria.

	N	QUANTILES					MEAN	STD. DEV	UPPER 95%	LOWER 95%
		100%	75%	50%	25%	0%				
DO	36	1.00	0.68	0.25	0.03	0.00	0.35	0.34	0.46	0.24
PO	36	1.00	0.86	0.53	0.17	0.00	0.52	0.36	0.65	0.40

The medians of AD for Digital Office and Physical Office were 0.25 and 0.53, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The comparison result showed that the null hypothesis can be rejected, hence there was a significant difference between these two groups (S=1490, Z=1.99, $p < 0.05$) (Table 6.15 and 6.16).

Table 6.16 Wilcoxon Non-Parametric Rank-Sum Test for AD Between Digital Office and Physical Office Samples

S	Z	Prob > |Z|
1490.00	1.99	0.05

6.3.2.3 Digital versus Physical

General Location

The General Location (GL) criterion was used to compare the gaming task results between the overall Digital and Physical. There were n=72 entries in each test group to be compared, the total number of entries was n=144.

Table 6.17 Quantiles and Summary Statistics of Participants' Results Based on GL Criteria.

	N	QUANTILES					MEAN	STD. DEV	UPPER 95%	LOWER 95%
		100%	75%	50%	25%	0%				
DIGITAL	72	1.00	1.00	0.70	0.40	0.00	0.68	0.30	0.75	0.61
PHYSICAL	72	1.00	1.00	1.00	0.70	0.20	0.83	0.23	0.89	0.78

The medians of GL for Digital and Physical were 0.7 and 1, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The comparison result showed that the null hypothesis can be rejected, hence there was a significant difference between these two groups ($S=6005.5$, $Z=3.29$, $p < 0.05$) (Table 6.17 and 6.18).

Table 6.18 Wilcoxon Non-Parametric Rank-Sum Test for GL Between Digital and Physical

S	Z	Prob > |Z|
6005.50	3.29	<0.01

Adjacency

The Adjacency (AD) criterion was used to compare the gaming task results between the overall Digital and Physical. There were n=72 entries in each test group to be compared, the total number of entries was n=144.

Table 6.19 Quantiles and Summary Statistics of Participants' Results Based on AD Criteria.

	N	QUANTILES					MEAN	STD. DEV	UPPER 95%	LOWER 95%
		100%	75%	50%	25%	0%				
DIGITAL	72	1.00	0.45	0.15	0.00	0.00	0.29	0.32	0.37	0.22
PHYSICAL	72	1.00	0.86	0.40	0.13	0.00	0.50	0.38	0.59	0.41

The medians of AD for Digital and Physical were 0.15 and 0.4, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The comparison result showed that the null hypothesis can be rejected, hence there was a significant difference between these two groups ($S=6071.5$, $Z=3.42$, $p < 0.05$) (Table 6.19 and 6.20).

Table 6.20 Wilcoxon Non-Parametric Rank-Sum Test for AD Between Digital and Physical

S	Z	Prob > |Z|
6071.50	3.42	<0.01

Exact Location

The Exact Location (EL) criterion was used to compare the gaming task results between the overall Digital and Physical. There were n=72 entries in each test group to be compared, the total number of entries was n=144.

Table 6.21 Quantiles and Summary Statistics of Participants' Results Based on EL Criteria.

	N	QUANTILES					MEAN	STD. DEV	UPPER 95%	LOWER 95%
		100%	75%	50%	25%	0%				
DIGITAL	72	1.00	0.50	0.10	0.00	0.00	0.34	0.29	0.41	0.27
PHYSICAL	72	1.00	0.80	0.50	0.20	0.00	0.50	0.32	0.57	0.42

The medians of EL for Digital and Physical were 0.3 and 0.5, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The comparison result showed that the null hypothesis can be rejected, hence there was a significant difference between these two groups ($S=5937.5$, $Z=2.88$, $p < 0.05$) (Table 6.21 and 6.22).

Table 6.22 Wilcoxon Non-Parametric Rank-Sum Test for EL Between Digital and Physical

S	Z	Prob > |Z|
5937.50	2.88	<0.01

6.3.3 Summary of Wilcoxon Rank-Sum Tests

6.3.3.1 Summary of Questionnaire Results

In general, comparisons between the questionnaire answers yielded only a few significant results.

All significant results came from Question 3: the overall level of difficulty of the gaming task. They can be summarized as follows:

- In the comparison between the combined digital and physical models, participants who studied the physical models generally found the tasks easier than those who studied the digital models.
- In the comparison between the house and office models, participants who studied the office models generally found the tasks easier than those who studied the house models.
- In the comparison between the digital house and digital office models, participants who studied the digital office models found the tasks easier than those who studied the digital house models.

6.3.3.2 Summary of Gaming Task Results

The overall digital versus physical analysis showed significant results in all three evaluation criteria. In general, participants who studied the physical models performed their tasks better than those who studied the digital models.

Similar results can be found when comparing the digital and physical house results. Participants who studied the physical house models performed better than those who studied the digital house models, relative to all three evaluation criteria.

In the comparison between the digital and physical offices, only the second criterion – Adjacency – showed that participants who studied the physical office performed better than those who studied the digital office models.

In general, I found no significant results after comparing the task results of the house versus office, physical house versus physical office, and digital house versus digital office models.

6.3.4 Multivariate Analysis of Correlation

A multivariate analysis of Pearson's correlation was conducted to find the relationships among the questionnaire answers and gaming task results, as well as the relationships across the questionnaire and task results.

Altogether, three questions and three evaluation criteria were compared (Figure 6.3). Although the Figure shows an exhaustive comparison between those six data sets, some data sets played more important roles than others in enabling the researcher to interpret this study (see Table 6.23).

Table 6.23 Pairwise Correlation Analysis with Significant Results

Variable	By variable	Correlation	Signif Prob
GL	Q2	-0.19	0.02
GL	Q3	-0.42	<0.01
AD	Q2	-0.27	<0.01
AD	Q3	-0.58	<0.01
EL	Q2	-0.25	<0.01
EL	Q3	-0.52	<0.01

- For the comparison between General Location (GL) and Q1, there was no correlation ($r= 0.01$, $p>0.05$).
- For the comparison between General Location (GL) and Q2, there was a negative correlation ($r= -0.19$, $p<0.05$).
- For the comparison between General Location (GL) and Q3, there was a negative correlation ($r= -0.42$, $p<0.01$).
- For the comparison between Adjacency (AD) and Q1, there was no correlation ($r= 0.07$, $p>0.05$).
- For the comparison between Adjacency (AD) and Q2, there was a negative correlation ($r= -0.27$, $p<0.01$).
- For the comparison between Adjacency (AD) and Q3, there was a negative correlation ($r= -0.58$, $p<0.01$).
- For the comparison between Exact Location (EL) and Q1, there was no correlation ($r= 0.00$, $p>0.05$).
- For the comparison between Exact Location (EL) and Q2, there was a negative correlation ($r= -0.25$, $p<0.01$).
- For the comparison between Exact Location (EL) and Q3, there was a negative correlation ($r= -0.52$, $p<0.01$).

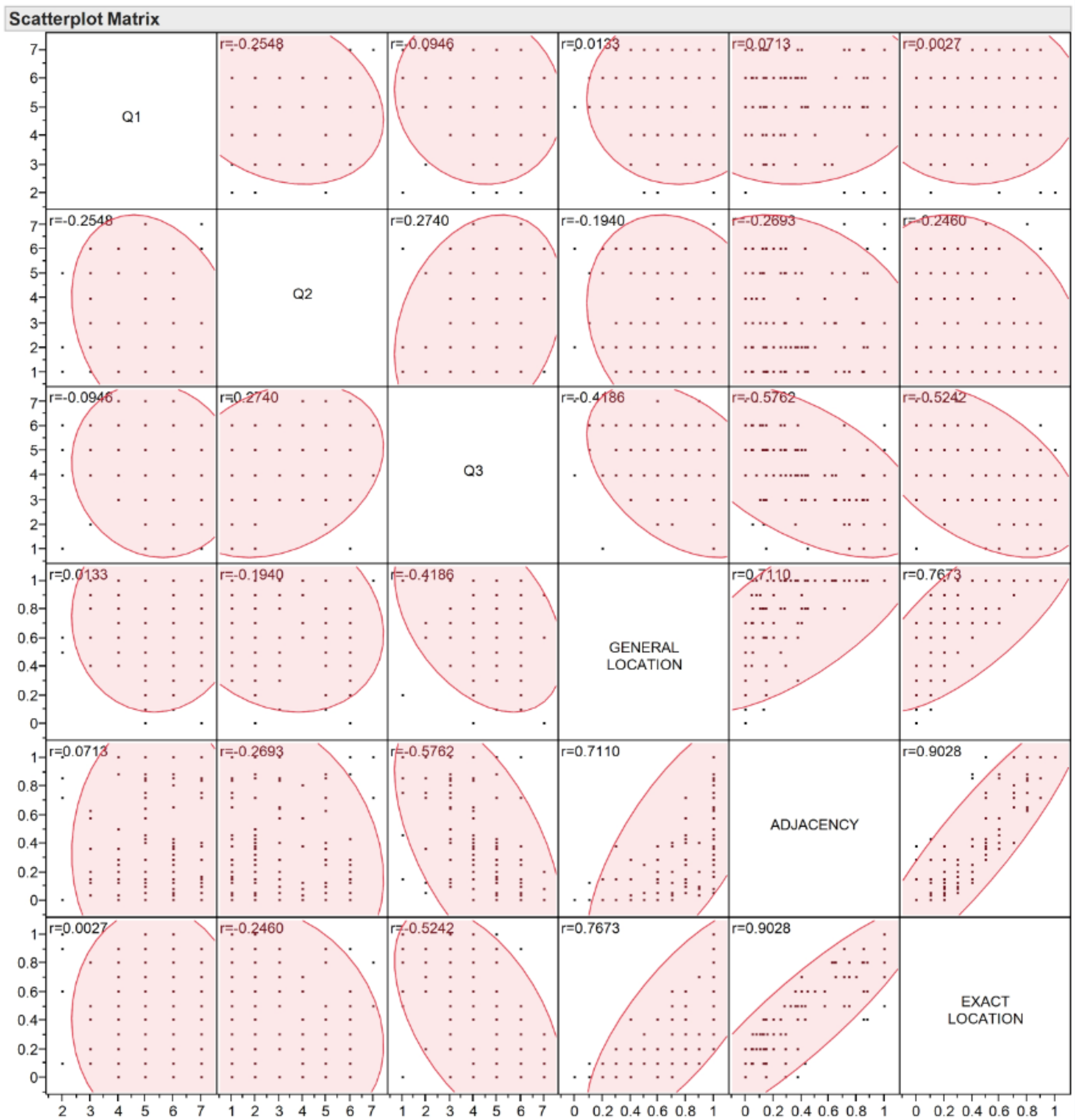

Figure 6.3 Pairwise Correlation Analysis Matrix

6.3.5 Summary of Multivariate Analysis

In general, I found no correlation between the pleasantness of the models and participants' gaming task results. However, the ease of manipulation was negatively correlated with all three evaluation criteria: the easier people found that they were able to manipulate the models, the better the results they achieved. Also, the level of difficulty was negatively correlated with all three evaluation criteria, which means that the easier people found the tasks, the better they performed.

CHAPTER VII

DISCUSSION

This chapter consists of three sections. The first discusses the results from the quantitative part of the study, the second discusses the results from the qualitative part of the study, and the third features a synthesis of the implications derived from both parts.

7.1 Discussion of Quantitative Results

While two types of buildings designed for the gaming tasks (single family home and office complex) show a certain level of sophistication – for example, the included fenestration and building site information – in order to illustrate their resemblance to actual buildings, they are also designed to be generic enough to represent a variety of scenarios and cover a broad range of building types. For the single family home model all geometries were closely arranged and interlocked, which can be seen as representing design situations in which the building components are adjacent to each other (for example, a project with multiple components located in a highly constrained site, or a design language the architect chooses to explore). For the office complex model, the geometries were arranged in a loose fashion compared to the house model, which can be seen as representing a larger-scale project with multiple buildings. At this scale of design, the architect aims to provide clients with a picture of the overall composition, rather than focusing on individual buildings and their details; this can also represent the master planning stage of a project, when the details of the design are not yet the center of concern.

Several significant results were found when evaluating participants' gaming task performances, using the three evaluation criteria described in Chapter III: General Location, Adjacency, and Exact Location.

The overall digital versus physical analysis showed significant results in all three evaluation criteria (see 6.3.2.3). In general, participants who studied physical models performed their tasks better than those who studied digital models. Similar results can be found if a further breakdown is undertaken by category, by comparing the physical house models to the digital house models. Participants who studied the physical house models performed their tasks better than those who studied the digital house models. This is an important finding, and it aligns with certain previous studies regarding the advantages of physical models in various aspects (e.g., Henry & Furness, 1993; Bliss et al., 1997; Wilson, 1997; Sun et al., 2013).

It should be noted that in a comparison of the physical office models to the digital office models, only the second evaluation criterion – Adjacency – showed a significant result; the participants who studied the physical office models performed better than those who studied the digital office models, and there were no significant differences between them with regards to General Location and Exact Location, the other two evaluation criteria (see 6.3.2.2). The Adjacency criterion evaluates people's understanding of the relationship between two adjacent geometries; thus, this result indicates that a physical model is a better medium if the interrelationship of building components is a key design concern. However, it also indicates that the type of project can play a role in the effectiveness of the media. One cannot simply conclude that physical models will exceed digital models in effectiveness without considering the design context.

When we add the factor of people's evaluations of their experiences with the models into the task results, a number of implications can be recognized. The correlation study revealed some especially interesting patterns with regards to the data. For instance, the first question from the questionnaire – How pleasant do you think the study model is? – had no correlation to any of the performance results as measured by General Location, Adjacency, and Exact Location; this indicates that how pleasant the models looked did not correlate to people's level of understanding in this particular experiment. On the other hand, answers from the second question – How easily can you manipulate the study model? – negatively correlated with all three evaluation criteria, which means the easier people feel it is to manipulate the models, the better the results they ultimately achieve.

In the overall comparison between physical and digital models, laypeople's self-evaluations of the third question – How difficult do you think the gaming task is? - correlated well with their performance; however, when looking at the results from the subcategories the comparison results become more complicated. Laypeople generally felt that the office models were easier to reconstruct than the house models, but the task results indicated no significant difference between the two. The different design configurations could play a role here: the more spread-out layout might appear to be easier to remember than the more compact, closely-grouped layout, though people's levels of understanding for each model remain on par with each other. A similar observation can be found when this category is further broken down, by comparing the digital house and office models; participants felt that the digital office models were easier to reconstruct, but again the test results showed no significant differences between them. The results of this comparison also align with previous findings.

7.2 Discussion of Qualitative Results

As discussed in the previous section, the results from the gaming tasks indicate that generally laypeople find physical models to be a better medium to help them understand three-dimensional layouts. This finding aligns with the ideas expressed by the architects who participated in the interviews. Many interviewees claimed that they found their clients better understood their projects by looking at physical models.

Architects reported that the reasons for a physical model’s superiority are manifold. Being “tactile” and “tangible” were some of the important characteristics shared by physical models, according to some architects. Being able to pick up and touch a model can greatly help clients to understand the design. Also, viewers don’t have to imagine the environment a model is in when looking at a physical model; the model shares the same environment as the viewers. On the other hand, digital models are rendered in a virtual environment with different background and lighting conditions; thus, they require extra brain power to process the scene.

“Sense of control” and being able to look at the models freely at any angle were also expressed by some interviewees as factors essential to their clients understanding a project. Architects mentioned that most of the interactive VE models currently used by architects were still desktop-based, and the human-machine interface was somewhat unintuitive to use; thus, it was impractical for their clients to learn to navigate through the models freely and by themselves. If better technologies are available in the future with more intuitive navigation interfaces, they may positively affect clients' experiences with these types of models.

However, we can conclude from interviewees' responses that the advantages of the physical models are not sufficient reason alone for architects to choose them over other media. Some characteristics of digital models still make them irreplaceable in many situations. They are generally easy to produce, easy to change, and easy to transfer. Digital models are also more helpful during the design process, according to some interviewees. They can be used to do quick studies and generate a number of design options in a relatively short amount of time, and this is especially helpful in high-demand situations.

Other than these factors, there were additional considerations reported by architects that might affect their decision making process when preparing for client meetings. Among them, project timeline and budget were two deciding factors. Since constructing physical models can be both costly and time consuming, architects may opt out of using physical models when designing smaller, simpler projects.

7.3 Synthesis of Results

When looking at quantitative and qualitative results side by side, several conclusions can be drawn.

The architects I interviewed were in consensus regarding the advantages of physical models over digital models. However, some interviewees discussed this comparison more carefully in the context of their own practices. Indeed, there has never been and likely will never be such a controlled environment for such a comparison in real world scenarios, so it's difficult to give a definite answer to this question in practice. A combined effort of both types of models is recommended to incorporate the best of both worlds, and thus help the client understand his or her design project in the best way possible.

Some architects reported that not being able to control a digital model could hinder one's ability to fully understand it. During the gaming tasks, participants were familiarized with navigation techniques using a mouse and keyboard. Their answers to the question – How easily can you manipulate the study model? – showed that there was no significant difference between those who manipulated the physical models and those who manipulated the digital models. This result shows that the human-machine interface for the desktop VE is easy enough for laypeople to learn and perform fluently in a very short amount of time; such a result could be associated with the heightened technology skills found in younger generations (Prensky, 2005). Consequently, these results indicate that ease of manipulation is not among the factors that make physical models easier to understand than digital models.

It should also be noted that statistics can reveal whether one treatment is better than another, but in real world scenarios, the client's requests must be addressed. Should a client prefer one medium over another, perhaps due to marketing, cost, or advertising issues, the architect must address their request. At the same time, it is useful for the architect, and perhaps his or her responsibility, to absorb the results of this research to inform his or her professional practice. Although statistically physical models were better than digital models for use in the gaming tasks, one cannot simply opt to use one over the other in design practice, since a best effort must be made to satisfy each client's own preferences and needs. In most cases, architects don't have the authority to direct their clients simply to accept anything; instead, clients have the freedom to choose the architect they feel will best meet their needs.

CHAPTER VIII

CONCLUSION

8.1 Summary

Effective communication between architects and clients is an important factor in ensuring a successful project. This study compared laypeople's understanding and preference with regards to digital and physical models, how these models are used in design practice, and how architects evaluate their clients' understanding and preferences.

The first phase of this study used a set of office complex and single family residence building models, represented in both physical and digital form, as the experiment instruments. The research adopted a quantitative methodology which compared desktop-based interactive 3-D architectural models to physical models by investigating laypeople's understanding of spatial layout and their preferences regarding use. Participants were asked to memorize the building components and reassemble them based on memory. The second phase of the study introduced a qualitative methodology with semi-structured interviews of eight practicing architects; this phase aimed at collecting the architects' opinions regarding their interactions with their clients and the models used to communicate design ideas.

In general, the results from the quantitative phase reveal that the laypeople who studied the physical models did a better job of reconstructing them than did those who studied the digital models. A series of breakdown results of each type of model were also discussed.

The qualitative phase of this research discussed a number of issues, including: (1) architects' use of and choice regarding models; (2) characteristics of different types of models, including merits and disadvantages; (3) factors that drive architects' decisions; (4) communication between architects and their clients; and (5) clients' ability to understand different types of architectural models.

8.2 Limitations

8.2.1 Choice of Models

The characteristics of physical and digital models are many; each have their strengths and weaknesses under different conditions, and both types can take many forms. For the quantitative experiment in this study, the focus was on people's understanding of spatial layout. Thus, the models were limited to volumetric expressions with only limited details; they were not detailed representations of real buildings. Some might argue that such models might not be sufficient to represent other types of projects, and also that the absence of materials and colors could cause problems for viewers hoping to envision an actual built environment. It should be noted that it was not the aim of this study to explore the specific properties of either type of model. The effectiveness of architectural models presented in alternative digital and physical forms, and those used in other contexts (for example, the ability of models to convey surface materials, color, or daylight illumination) cannot be justified based on the findings of this study. Given the broad range of different types of models, additional studies are required to reveal other conclusions about the media.

8.2.2 Sample

The sample population in the quantitative part of this study consists only of undergraduate students. Some may argue that a sample from the younger generation might not be a sufficient representation of the laypeople population at large (Persky, 2005).

8.2.3 Scale

People might also question the scale of the physical models used in this study; the choices of 1”= 8’- 0” and 1”= 16’- 0” may not cover other scenarios when different scales are presented. Architects use many different scales for their physical models during different design stages; their choice of scale may depend upon different project sizes and the level of detail the architect wants to produce. Historically, researchers have used a variety of scales in their environmental simulation studies regarding people's judgments, but the ability to predict the real environment was not skewed in any particular scale, so long as there was enough detail in the models to identify the buildings' characteristics (De Long, 1976; Feimer, 1984; Seaton & Collins, 1972).

8.2.4 Qualitative Methodology

Qualitative methodology is often critically evaluated with regards to issues of external validity and generalizability. The small sample size is believed to render it difficult to extrapolate the findings to a more generalized population; thus, it may not be accepted by empirical and logical examinations (Myers, 2000). The reliability of qualitative research is also a point of concern, since it is difficult to replicate the observations made if they are performed by another investigator taking a valid yet different approach (Kirk & Miller, 1986). In terms of objectivity, some studies pointed out that the presence of the researcher could affect the reactions of the subjects, and thus that bias is inevitable (Schaffir & Stebbins, 1991).

8.3 Recommendations for Future Research

8.3.1 The Models

The models used in this study can be further developed to simulate a more detailed built environment. Currently, the models were designed to be simple and straightforward; although indications of fenestration were included, the model pieces were still somewhat abstract. Further study regarding how different levels of detail affect people's understanding of the built environment is needed.

8.3.2 Reconstruction Process

It would be beneficial to see how laypeople memorize the spatial layouts and carry out their gaming tasks (for example, the way they construct the models and the priority of the block placement). During this study, I took some field notes on this topic recording my own observations, but a more reliable and comprehensive method that could be analyzed quantitatively would be more desirable. An understanding of their process is important in order to further explore the inherent properties of the different types of models. Video recording the gaming tasks is recommended in future inquiries regarding this subject matter.

8.3.3 The Instruments

Although cuboids have been used by previous researchers to study people's understanding of spatial layouts, the instruments and the evaluation criteria used in this study were developed specifically to fit into the architectural design context. Further refinement of the instruments and evaluation criteria is needed to improve their effectiveness in such a research context.

8.3.4 Interviewees

Furthermore, a more diverse group of architects should be interviewed in future studies to draw a better picture of the profession. Some firms are more specialized in certain types of projects, while some firms are more general and cover a broader range of projects; some are large with an international presence, and some are small and only serve local clients. They are all important contributors to the profession and each type of firm may see the practice in a different way. A more comprehensive understanding of the industry is needed.

8.4 Implications for Professional Practice

From a design practice standpoint, many factors are in play when choosing a presentation medium. However, in general, using a physical model may offer the best chance of helping a client understand a project, given it is produced with the necessary level of detail that the design phase and project progress allow.

When the choice is limited to digital media, one should note that the level of detail may play an important role in helping a client to understand the model. Meanwhile, a sense of control might also be a helpful factor in conveying design ideas in virtual spaces. An instrument that allows clients to wander freely inside a model, rather than simply view a model controlled by the presenters, may also be a beneficial tool in helping people understand a design. Current affordable human-machine interfaces are still not intuitive enough to perform these tasks, but such technology should be kept in mind whenever it does become available.

After all, if time, budget, and resources are available, the best results may be achieved by a combined effort of both physical and digital media, so the advantages of each medium can be fully utilized.

8.5 Conclusion

In the context of quantitative methodology, only in an ideal setting with well-controlled environments and variables can the effectiveness of physical versus digital models be studied. However, the dynamics and complexity of architectural practice may render lab results insufficient. The quantitative part of the study is not meant to be used as a prescriptive guideline for practice, but rather to provide information and, hopefully, insights to architects considering different strategies for client meetings. A comprehensive evaluation is still needed for each project (for example, the preferences of clients, types of designs presented, level of detail at a particular design stage, etc.) to better facilitate architect-client communication.

The architectural practice is constantly evolving. New technologies, ever-changing social, political and economic milieu, as well as client demands can all rapidly alter its direction. Today’s science fiction could become tomorrow’s daily norm. As a researcher who embraces the entire context of the architectural profession, it is essential to remain vigilant and always be aware of new trends and directions, then properly adjust one’s strategies to accommodate new situations.

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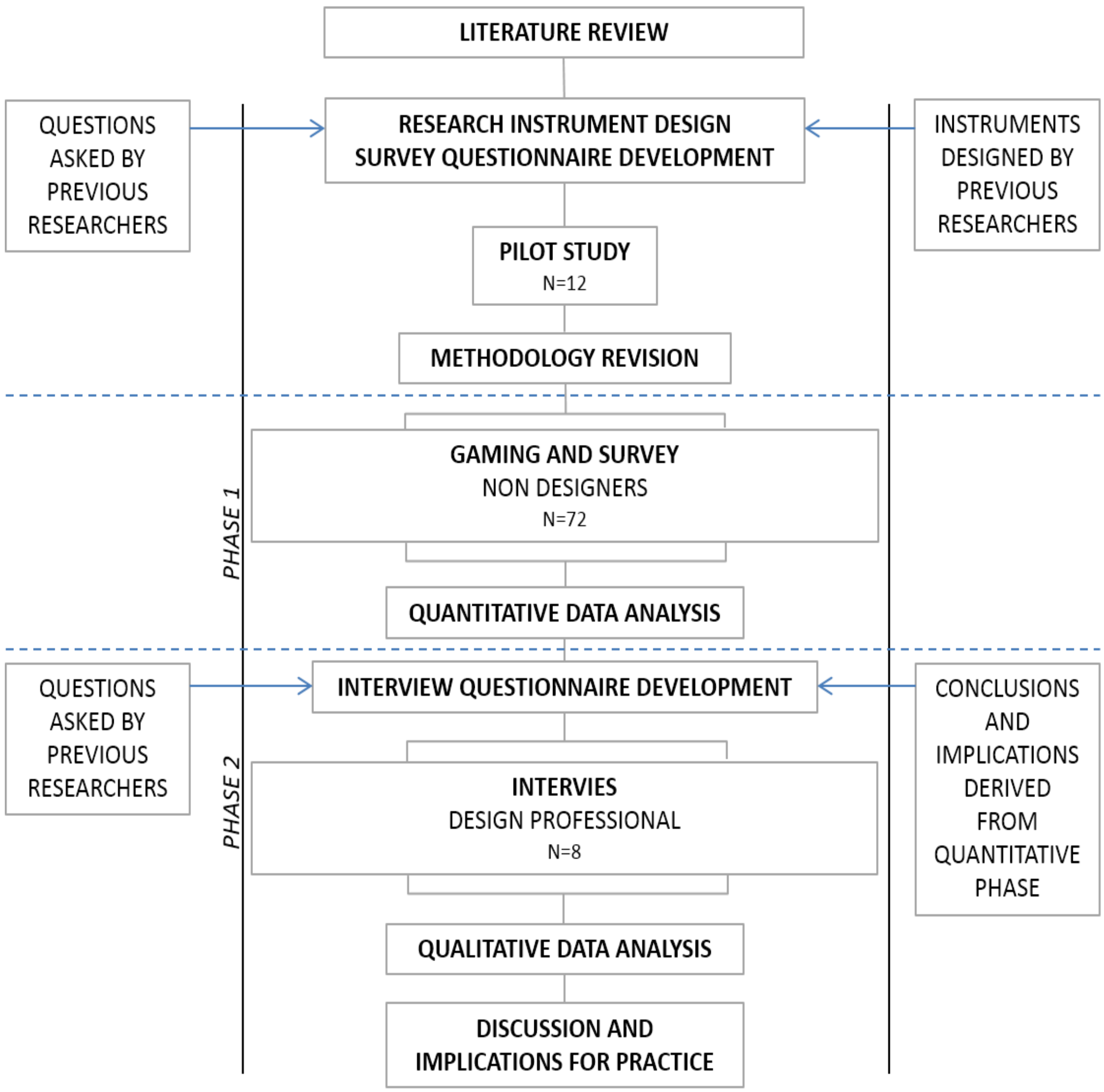
APPENDIX A: OVERVIEW DIAGRAM OF RESEARCH FRAMEWORK



APPENDIX B: QUESTIONANIRE ANSWERS AND GAMING TASK RESULTS

Questionnaire Answers

1. Digital Houses versus Physical Houses

Unpleasant – Pleasant

Outcomes of the two seven-point Likert Scale questionnaire answers regarding the question - How pleasant does the study model look? - were compared using the Wilcoxon two-sample Rank-Sum test. There were n=36 entries in each test group to be compared, the total number of entries was n=72.

Table B.1 Quantiles and Summary Statistics of Participants' Response of Q1. Left: Digital House; Right: Physical House

Quantiles		Digital House	Physical House
100.0%	maximum	7	7
99.5%		7	7
97.5%		7	7
90.0%		6	7
75.0%	quartile	6	6
50.0%	median	5	6
25.0%	quartile	4	4.25
10.0%		3	4
2.5%		2	3
0.5%		2	3
0.0%	minimum	2	3

Summary Statistics	Digital House	Physical House
Mean	4.9444444	5.4444444
Std Dev	1.2636556	1.1069764
Std Err Mean	0.2106093	0.1844961
Upper 95% Mean	5.372004	5.8189914
Lower 95% Mean	4.5168849	5.0698975
N	36	36

The medians for Q1 regarding the digital house and physical house were 5 and 6, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for DH and PH were 1,177 and 1,451, and the mean scores were 32.69 and 40.31. The comparison results showed that the null hypothesis could not be rejected; hence, there was no significant difference between these two groups (S=1451, Z=1.60, $p > 0.05$) (see Tables B.1 & B.2).

Table B.2 Wilcoxon Non-Parametric Rank-Sum Test for Q1 Between Digital House and Physical House Samples

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
DH	36	1177.00	1314.00	32.6944	-1.595
PH	36	1451.00	1314.00	40.3056	1.595

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
1451	1.59535	0.1106

Easy to Manipulate – Difficult to Manipulate

Outcomes of the two seven-point Likert Scale questionnaire answers regarding the question - How easily can you manipulate the study model? - were compared using the Wilcoxon two-sample Rank-Sum test. There were n=36 entries in each test group to be compared, the total number of entries was n=72.

Table B.3 Quantiles and Summary Statistics of Participants' Response of Q2. Left: Digital House; Right: Physical House

Quantiles (Digital House)

100.0%	maximum	7
99.5%		7
97.5%		7
90.0%		6
75.0%	quartile	5
50.0%	median	3
25.0%	quartile	1.25
10.0%		1
2.5%		1
0.5%		1
0.0%	minimum	1

Summary Statistics (Digital House)

Mean	3.2777778
Std Dev	1.9065468
Std Err Mean	0.3177578
Upper 95% Mean	3.9228604
Lower 95% Mean	2.6326952
N	36

Quantiles (Physical House)

100.0%	maximum	6
99.5%		6
97.5%		6
90.0%		5
75.0%	quartile	3
50.0%	median	2
25.0%	quartile	1
10.0%		1
2.5%		1
0.5%		1
0.0%	minimum	1

Summary Statistics (Physical House)

Mean	2.5
Std Dev	1.4442002
Std Err Mean	0.2407
Upper 95% Mean	2.9886471
Lower 95% Mean	2.0113529
N	36

The medians of Q2 for Digital house and Physical house were 3 and 2 respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for DH and PH were 1457 and 1171, and the score mean were 40.47 and 32.53. The comparison result showed that the null hypothesis cannot be rejected, hence there was no significant difference between these two groups (S=1171, Z=-1.64, p > 0.05) (Table B.3 & Table B.4).

Table B.4 Wilcoxon Non-Parametric Rank-Sum Test for Q2 Between Digital House and Physical House Samples

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
DH	36	1457.00	1314.00	40.4722	1.641
PH	36	1171.00	1314.00	32.5278	-1.641

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
1171	-1.64141	0.1007

Overall Difficulty: Easy – Difficult

Outcomes of the two seven-point Likert Scale questionnaire answers regarding the question - How easy do you think the gaming task is? - were compared using the Wilcoxon two-sample Rank-Sum test. There were n=36 entries in each test group to be compared, the total number of entries was n=72.

Table B.5 Quantiles and Summary Statistics of Participants' Response of Q3. Left: Digital House; Right: Physical House

Quantiles

		Digital House	Physical House
100.0%	maximum	7	7
99.5%		7	7
97.5%		7	7
90.0%		6	6
75.0%	quartile	6	5
50.0%	median	5	4
25.0%	quartile	4	3
10.0%		3	2
2.5%		1	1
0.5%		1	1
0.0%	minimum	1	1

Summary Statistics

	Digital House	Physical House
Mean	4.7777778	4.1666667
Std Dev	1.3545924	1.4040757
Std Err Mean	0.2257654	0.2340126
Upper 95% Mean	5.2361059	4.6417375
Lower 95% Mean	4.3194496	3.6915958
N	36	36

The medians of Q3 for Digital house and Physical house were 5 and 4 respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for DH and PH were 1482.50 and 1145.50, and the score mean were 41.18 and 31.82. The comparison result showed that the null hypothesis cannot be rejected, hence there was no significant difference between these two groups (S=1145.5, Z=-1.94, $p > 0.05$) (Table B.5 & Table B.6).

Table B.6 Wilcoxon Non-Parametric Rank-Sum Test for Q3 between Digital House and Physical House Samples

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
DH	36	1482.50	1314.00	41.1806	1.936
PH	36	1145.50	1314.00	31.8194	-1.936

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
1145.5	-1.93616	0.0528

2. Digital Offices versus Physical Offices

Unpleasant – Pleasant

Outcomes of the two seven-point Likert Scale questionnaire answers regarding the question – How pleasant does the study model look? - were compared using the Wilcoxon two-sample Rank-Sum test. There were n=36 entries in each test group to be compared, the total number of entries was n=72.

Table B.7 Quantiles and Summary Statistics of Participants' Response of Q1. Left: Digital Office; Right: Physical Office

Quantiles

		Digital Office	Physical Office
100.0%	maximum	7	7
99.5%		7	7
97.5%		7	7
90.0%		7	7
75.0%	quartile	6	6
50.0%	median	6	6
25.0%	quartile	5	5
10.0%		3	4
2.5%		2	2
0.5%		2	2
0.0%	minimum	2	2

Summary Statistics

	Digital Office	Physical Office
Mean	5.4166667	5.5555556
Std Dev	1.3809934	1.1324927
Std Err Mean	0.2301656	0.1887488
Upper 95% Mean	5.8839276	5.938736
Lower 95% Mean	4.9494057	5.1723752
N	36	36

The medians of Q1 for Digital office and Physical office were both 6. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for DO and PO were 1307.00 and 1321.00, and the score mean were 36.31 and 36.69. The comparison result showed that the null hypothesis cannot be rejected, hence there was no significant difference between these two groups ($S=1321$, $Z=0.08$, $p > 0.05$) (Table B.7 & Table B.8).

Table B.8 Wilcoxon Non-Parametric Rank-Sum Test for Q1 Between Digital Office and Physical Office Samples

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
DO	36	1307.00	1314.00	36.3056	-0.076
PO	36	1321.00	1314.00	36.6944	0.076

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
1321	0.07642	0.9391

Easy to Manipulate – Difficult to Manipulate

Outcomes of the two seven-point Likert Scale questionnaire answers regarding the question – How easily can you manipulate the study model? - were compared using the Wilcoxon two-sample Rank-Sum test. There were n=36 entries in each test group to be compared, the total number of entries was n=72.

Table B.9 Quantiles and Summary Statistics of Participants' Response of Q2. Left: Digital Office; Right: Physical Office

Quantiles (Left: Digital Office)

100.0%	maximum	7
99.5%		7
97.5%		7
90.0%		6
75.0%	quartile	5.75
50.0%	median	2
25.0%	quartile	1
10.0%		1
2.5%		1
0.5%		1
0.0%	minimum	1

Summary Statistics

Mean	3.1666667
Std Dev	2.0632845
Std Err Mean	0.3438807
Upper 95% Mean	3.8647817
Lower 95% Mean	2.4685516
N	36

Quantiles (Right: Physical Office)

100.0%	maximum	6
99.5%		6
97.5%		6
90.0%		5.3
75.0%	quartile	5
50.0%	median	2
25.0%	quartile	1
10.0%		1
2.5%		1
0.5%		1
0.0%	minimum	1

Summary Statistics

Mean	2.8888889
Std Dev	1.7853015
Std Err Mean	0.2975503
Upper 95% Mean	3.492948
Lower 95% Mean	2.2848298
N	36

The medians of Q2 for Digital office and Physical office were both 2. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for DO and PO were 1369.00 and 1259.00, and the score mean were 38.03 and 34.97. The comparison result showed that the null hypothesis cannot be rejected, hence there was no significant difference between these two groups (S=1259, Z=-0.63, p > 0.05) (Table B.9 & Table B.10).

Table B.10 Wilcoxon Non-Parametric Rank-Sum Test for Q1 Between Digital Office and Physical Office Samples

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
DO	36	1369.00	1314.00	38.0278	0.629
PO	36	1259.00	1314.00	34.9722	-0.629

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
1259	-0.62889	0.5294

Overall Difficulty: Easy – Difficult

Outcomes of the two seven-point Likert Scale questionnaire answers regarding the question – How easy do you think the gaming task is? - were compared using the Wilcoxon two-sample Rank-Sum test. There were n=36 entries in each test group to be compared, the total number of entries was n=72.

Table B.11 Quantiles and Summary Statistics of Participants' Response of Q3. Left: Digital Office; Right: Physical Office

Quantiles

		Digital Office	Physical Office
100.0%	maximum	7	6
99.5%		7	6
97.5%		7	6
90.0%		6	6
75.0%	quartile	5	5
50.0%	median	4	4
25.0%	quartile	3	3
10.0%		1.7	2
2.5%		1	1
0.5%		1	1
0.0%	minimum	1	1

Summary Statistics

	Digital Office	Physical Office
Mean	4.1111111	3.7777778
Std Dev	1.4496852	1.45624
Std Err Mean	0.2416142	0.2427067
Upper 95% Mean	4.601614	4.2704985
Lower 95% Mean	3.6206082	3.2850571
N	36	36

The medians of Q3 for Digital office and Physical office were both 4. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for DO and PO were 1409.00 and 1219.00, and the score mean were 39.14 and 33.86. The comparison result showed that the null hypothesis cannot be rejected, hence there was no significant difference between these two groups ($S=1219$, $Z=-1.09$, $p > 0.05$) (Table B.11 & Table B.12).

Table B.12 Wilcoxon Non-Parametric Rank-Sum Test for Q3 Between Digital Office and Physical Office Samples

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
DO	36	1409.00	1314.00	39.1389	1.087
PO	36	1219.00	1314.00	33.8611	-1.087

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
1219	-1.08679	0.2771

3. Digital Houses versus Digital Offices

Unpleasant – Pleasant

Outcomes of the two seven-point Likert Scale questionnaire answers regarding the question – How pleasant does the study model look? - were compared using the Wilcoxon two-sample Rank-Sum test. There were n=36 entries in each test group to be compared, the total number of entries was n=72.

Table B.13 Quantiles and Summary Statistics of Participants' Response of Q1. Left: Digital House; Right: Digital Office

Quantiles		Digital House	Digital Office
100.0%	maximum	7	7
99.5%		7	7
97.5%		7	7
90.0%		6	7
75.0%	quartile	6	6
50.0%	median	5	6
25.0%	quartile	4	5
10.0%		3	3
2.5%		2	2
0.5%		2	2
0.0%	minimum	2	2

Summary Statistics	Digital House	Digital Office
Mean	4.9444444	5.4166667
Std Dev	1.2636556	1.3809934
Std Err Mean	0.2106093	0.2301656
Upper 95% Mean	5.372004	5.8839276
Lower 95% Mean	4.5168849	4.9494057
N	36	36

The medians of Q1 for Digital office and Physical office were 5 and 6, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for DH and DO were 1157.00 and 1471.00, and the score mean were 32.14 and 40.86. The comparison result showed that the null hypothesis cannot be rejected, hence there was no significant difference between these two groups (S=1471, Z=1.83, $p > 0.05$) (Table B.13 & Table B.14).

Table B.14 Wilcoxon Non-Parametric Rank-Sum Test for Q1 Between Digital House and Digital Office Samples

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
DH	36	1157.00	1314.00	32.1389	-1.829
DO	36	1471.00	1314.00	40.8611	1.829

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
1471	1.82852	0.0675

Easy to Manipulate – Difficult to Manipulate

Outcomes of the two seven-point Likert Scale questionnaire answers regarding the question – How easily can you manipulate the study model? - were compared using the Wilcoxon two-sample Rank-Sum test. There were n=36 entries in each test group to be compared, the total number of entries was n=72.

Table B.15 Quantiles and Summary Statistics of Participants' Response of Q2. Left: Digital House; Right: Digital Office

Quantiles

		Digital House	Digital Office
100.0%	maximum	7	7
99.5%		7	7
97.5%		7	7
90.0%		6	6
75.0%	quartile	5	5.75
50.0%	median	3	2
25.0%	quartile	1.25	1
10.0%		1	1
2.5%		1	1
0.5%		1	1
0.0%	minimum	1	1

Summary Statistics

	Digital House	Digital Office
Mean	3.2777778	3.1666667
Std Dev	1.9065468	2.0632845
Std Err Mean	0.3177578	0.3438807
Upper 95% Mean	3.9228604	3.8647817
Lower 95% Mean	2.6326952	2.4685516
N	36	36

The medians of Q2 for Digital office and Physical office were 3 and 2, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for DH and DO were 1338.00 and 1290.00, and the score mean were 37.17 and 35.83. The comparison result showed that the null hypothesis cannot be rejected, hence there was no significant difference between these two groups (S=1290, Z=-0.27, p > 0.05) (Table B.15 & Table B.16).

Table B.16 Wilcoxon Non-Parametric Rank-Sum Test for Q2 Between Digital House and Digital Office Samples

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
DH	36	1338.00	1314.00	37.1667	0.270
DO	36	1290.00	1314.00	35.8333	-0.270

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
1290	-0.26983	0.7873

Overall Difficulty: Easy – Difficult

Outcomes of the two seven-point Likert Scale questionnaire answers regarding the question – How easy do you think the gaming task is? - were compared using the Wilcoxon two-sample Rank-Sum test. There were n=36 entries in each test group to be compared, the total number of entries was n=72.

Table B.17 Quantiles and Summary Statistics of Participants' Response of Q3. Left: Digital House; Right: Digital Office

Quantiles

100.0%	maximum	7	100.0%	maximum	7
99.5%		7	99.5%		7
97.5%		7	97.5%		7
90.0%		6	90.0%		6
75.0%	quartile	6	75.0%	quartile	5
50.0%	median	5	50.0%	median	4
25.0%	quartile	4	25.0%	quartile	3
10.0%		3	10.0%		1.7
2.5%		1	2.5%		1
0.5%		1	0.5%		1
0.0%	minimum	1	0.0%	minimum	1

Summary Statistics

Mean	4.7777778	Mean	4.1111111
Std Dev	1.3545924	Std Dev	1.4496852
Std Err Mean	0.2257654	Std Err Mean	0.2416142
Upper 95% Mean	5.2361059	Upper 95% Mean	4.601614
Lower 95% Mean	4.3194496	Lower 95% Mean	3.6206082
N	36	N	36

The medians of Q3 for Digital office and Physical office were 5 and 4, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for DH and DO were 1491.00 and 1137.00, and the score mean were 41.42 and 31.58. The comparison result showed that the null hypothesis can be rejected, hence there was a significant difference between these two groups ($S=1137$, $Z=-2.04$, $p < 0.05$) (Table B.17 & Table B.18).

Table B.18 Wilcoxon Non-Parametric Rank-Sum Test for Q3 Between Digital House and Digital Office Samples

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
DH	36	1491.00	1314.00	41.4167	2.040
DO	36	1137.00	1314.00	31.5833	-2.040

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
1137	-2.03997	0.0414*

4. Physical Houses versus Physical Offices

Unpleasant – Pleasant

Outcomes of the two seven-point Likert Scale questionnaire answers regarding the question – How pleasant does the study model look? - were compared using the Wilcoxon two-sample Rank-Sum test. There were n=36 entries in each test group to be compared, the total number of entries was n=72.

Table B.19 Quantiles and Summary Statistics of Participants' Response of Q1. Left: Physical House; Right: Physical Office

Quantiles

		Physical House	Physical Office
100.0%	maximum	7	7
99.5%		7	7
97.5%		7	7
90.0%		7	7
75.0%	quartile	6	6
50.0%	median	6	6
25.0%	quartile	4.25	5
10.0%		4	4
2.5%		3	2
0.5%		3	2
0.0%	minimum	3	2

Summary Statistics

	Physical House	Physical Office
Mean	5.4444444	5.5555556
Std Dev	1.1069764	1.1324927
Std Err Mean	0.1844961	0.1887488
Upper 95% Mean	5.8189914	5.938736
Lower 95% Mean	5.0698975	5.1723752
N	36	36

The medians of Q1 for Digital office and Physical office were both 6. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for PH and PO were 1271.50 and 1356.50, and the score mean were 35.32 and 37.68. The comparison result showed that the null hypothesis cannot be rejected, hence there was no significant difference between these two groups (S=1356.5, Z=0.49, $p > 0.05$) (Table B.19 & Table B.20).

Table B.20 Wilcoxon Non-Parametric Rank-Sum Test for Q1 Between Physical House and Physical Office Samples

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
PH	36	1271.50	1314.00	35.3194	-0.493
PO	36	1356.50	1314.00	37.6806	0.493

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
1356.5	0.49303	0.6220

Easy to Manipulate – Difficult to Manipulate

Outcomes of the two seven-point Likert Scale questionnaire answers regarding the question – How easily can you manipulate the study model? - were compared using the Wilcoxon two-sample Rank-Sum test. There were n=36 entries in each test group to be compared, the total number of entries was n=72.

Table B.21 Quantiles and Summary Statistics of Participants' Response of Q2. Left: Physical House; Right: Physical Office

Quantiles (Left: Physical House)

100.0%	maximum	6
99.5%		6
97.5%		6
90.0%		5
75.0%	quartile	3
50.0%	median	2
25.0%	quartile	1
10.0%		1
2.5%		1
0.5%		1
0.0%	minimum	1

Summary Statistics

Mean	2.5
Std Dev	1.4442002
Std Err Mean	0.2407
Upper 95% Mean	2.9886471
Lower 95% Mean	2.0113529
N	36

Quantiles (Right: Physical Office)

100.0%	maximum	6
99.5%		6
97.5%		6
90.0%		5.3
75.0%	quartile	5
50.0%	median	2
25.0%	quartile	1
10.0%		1
2.5%		1
0.5%		1
0.0%	minimum	1

Summary Statistics

Mean	2.8888889
Std Dev	1.7853015
Std Err Mean	0.2975503
Upper 95% Mean	3.492948
Lower 95% Mean	2.2848298
N	36

The medians of Q2 for Digital office and Physical office were both 2. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for PH and PO were 1260.00 and 1368.00, and the score mean were 35.00 and 38.00. The comparison result showed that the null hypothesis cannot be rejected, hence there was no significant difference between these two groups (S=1368.5, Z=0.62, p > 0.05) (Table B.21 & Table B.22).

Table B.22 Wilcoxon Non-Parametric Rank-Sum Test for Q2 Between Physical House and Physical Office Samples

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
PH	36	1260.00	1314.00	35.0000	-0.620
PO	36	1368.00	1314.00	38.0000	0.620

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
1368	0.62032	0.5350

Overall Difficulty: Easy – Difficult

Outcomes of the two seven-point Likert Scale questionnaire answers regarding the question – How easy do you think the gaming task is? - were compared using the Wilcoxon two-sample Rank-Sum test. There were n=36 entries in each test group to be compared, the total number of entries was n=72.

Table B.23 Quantiles and Summary Statistics of Participants' Response of Q3. Left: Physical House; Right: Physical Office

Quantiles

100.0%	maximum	7
99.5%		7
97.5%		7
90.0%		6
75.0%	quartile	5
50.0%	median	4
25.0%	quartile	3
10.0%		2
2.5%		1
0.5%		1
0.0%	minimum	1

Summary Statistics

Mean	4.1666667
Std Dev	1.4040757
Std Err Mean	0.2340126
Upper 95% Mean	4.6417375
Lower 95% Mean	3.6915958
N	36

Quantiles

100.0%	maximum	6
99.5%		6
97.5%		6
90.0%		6
75.0%	quartile	5
50.0%	median	4
25.0%	quartile	3
10.0%		2
2.5%		1
0.5%		1
0.0%	minimum	1

Summary Statistics

Mean	3.7777778
Std Dev	1.45624
Std Err Mean	0.2427067
Upper 95% Mean	4.2704985
Lower 95% Mean	3.2850571
N	36

The medians of Q3 for Digital office and Physical office were both 4. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for PH and PO were 1411.00 and 1217.00, and the score mean were 39.19 and 33.81. The comparison result showed that the null hypothesis cannot be rejected, hence there was no significant difference between these two groups (S=1217, Z=-1.11, p > 0.05) (Table B.23 & Table B.24).

Table B.24 Wilcoxon Non-Parametric Rank-Sum Test for Q3 Between Physical House and Physical Office Samples

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
PH	36	1411.00	1314.00	39.1944	1.110
PO	36	1217.00	1314.00	33.8056	-1.110

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
1217	-1.10955	0.2672

5. Digital versus Physical

Unpleasant – Pleasant

Outcomes of the two seven-point Likert Scale questionnaire answers regarding the question – How pleasant does the study model look? - were compared using the Wilcoxon two-sample Rank-Sum test. There were n=72 entries in each test group to be compared, the total number of entries was n=144.

Table B.25 Quantiles and Summary Statistics of Participants' Response of Q1. Left: Digital; Right: Physical

Quantiles (Left: Digital)

100.0%	maximum	7
99.5%		7
97.5%		7
90.0%		7
75.0%	quartile	6
50.0%	median	5.5
25.0%	quartile	4
10.0%		3
2.5%		2
0.5%		2
0.0%	minimum	2

Summary Statistics (Left: Digital)

Mean	5.1805556
Std Dev	1.3356055
Std Err Mean	0.1574026
Upper 95% Mean	5.4944075
Lower 95% Mean	4.8667037
N	72

Quantiles (Right: Physical)

100.0%	maximum	7
99.5%		7
97.5%		7
90.0%		7
75.0%	quartile	6
50.0%	median	6
25.0%	quartile	5
10.0%		4
2.5%		2.825
0.5%		2
0.0%	minimum	2

Summary Statistics (Right: Physical)

Mean	5.5
Std Dev	1.1132999
Std Err Mean	0.1312036
Upper 95% Mean	5.7616126
Lower 95% Mean	5.2383874
N	72

The medians of Q1 for Digital and Physical were 5.5 and 6, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for D and P were 4920.50 and 5519.50, and the score mean were 68.34 and 76.66. The comparison result showed that the null hypothesis cannot be rejected, hence there was no significant difference between these two groups ($S=5519.5$, $Z=1.24$, $p > 0.05$) (Table B.25 & Table B.26).

Table B.26 Wilcoxon Non-Parametric Rank-Sum Test for Q1 Between Physical House and Physical Office Samples

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
DIGITAL	72	4920.50	5220.00	68.3403	-1.242
PHYSICAL	72	5519.50	5220.00	76.6597	1.242

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
5519.5	1.24196	0.2143

Easy to Manipulate – Difficult to Manipulate

Outcomes of the two seven-point Likert Scale questionnaire answers regarding the question – How easily can you manipulate the study model? - were compared using the Wilcoxon two-sample Rank-Sum test. There were n=72 entries in each test group to be compared, the total number of entries was n=144.

Table B.27 Quantiles and Summary Statistics of Participants' Response of Q2. Left: Digital; Right: Physical

Quantiles

		Digital	Physical
100.0%	maximum	7	6
99.5%		7	6
97.5%		7	6
90.0%		6	5
75.0%	quartile	5	4
50.0%	median	3	2
25.0%	quartile	1	1
10.0%		1	1
2.5%		1	1
0.5%		1	1
0.0%	minimum	1	1

Summary Statistics

	Digital	Physical
Mean	3.2222222	2.6944444
Std Dev	1.9732166	1.6241044
Std Err Mean	0.2325458	0.1914025
Upper 95% Mean	3.6859054	3.0760903
Lower 95% Mean	2.7585391	2.3127986
N	72	72

The medians of Q2 for Digital and Physical were 3 and 2, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for D and P were 5591.00 and 4849.00, and the score mean were 77.65 and 67.35. The comparison result showed that the null hypothesis cannot be rejected, hence there was no significant difference between these two groups (S=4849, Z=-1.51, p > 0.05) (Table B.27 & Table B.28).

Table B.28 Wilcoxon Non-Parametric Rank-Sum Test for Q2 Between Physical House and Physical Office Samples

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
DIGITAL	72	5591.00	5220.00	77.6528	1.514
PHYSICAL	72	4849.00	5220.00	67.3472	-1.514

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
4849	-1.51427	0.1300

Overall Difficulty: Easy – Difficult

Outcomes of the two seven-point Likert Scale questionnaire answers regarding the question – How easy do you think the gaming task is? - were compared using the Wilcoxon two-sample Rank-Sum test. There were n=72 entries in each test group to be compared, the total number of entries was n=144.

Table B.29 Quantiles and Summary Statistics of Participants' Response of Q3. Left: Digital; Right: Physical

Quantiles		Digital	Physical
100.0%	maximum	7	7
99.5%		7	7
97.5%		7	6.175
90.0%		6	6
75.0%	quartile	5	5
50.0%	median	5	4
25.0%	quartile	4	3
10.0%		3	2
2.5%		1	1
0.5%		1	1
0.0%	minimum	1	1

Summary Statistics	Digital	Physical
Mean	4.4444444	3.9722222
Std Dev	1.432902	1.4337209
Std Err Mean	0.1688691	0.1689656
Upper 95% Mean	4.7811599	4.3091301
Lower 95% Mean	4.107729	3.6353143
N	72	72

The medians of Q2 for Digital and Physical were 5 and 4, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for D and P were 5734.00 and 4706.00, and the score mean were 79.64 and 65.36. The comparison result showed that the null hypothesis can be rejected, hence there was a significant difference between these two groups ($S=4706$, $Z=-2.10$, $p < 0.05$) (Table B.29 & Table B.30).

Table B.30 Wilcoxon Non-Parametric Rank-Sum Test for Q3 Between Physical House and Physical Office Samples

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
DIGITAL	72	5734.00	5220.00	79.6389	2.095
PHYSICAL	72	4706.00	5220.00	65.3611	-2.095

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
4706	-2.09530	0.0361*

6. Houses versus Offices

Unpleasant – Pleasant

Outcomes of the two seven-point Likert Scale questionnaire answers regarding the question – How pleasant does the study model look? - were compared using the Wilcoxon two-sample Rank-Sum test. There were n=72 entries in each test group to be compared, the total number of entries was n=144.

Table B.31 Quantiles and Summary Statistics of Participants' Response of Q1. Left: House; Right: Office

Quantiles (House)

100.0%	maximum	7
99.5%		7
97.5%		7
90.0%		7
75.0%	quartile	6
50.0%	median	5
25.0%	quartile	4
10.0%		4
2.5%		2
0.5%		2
0.0%	minimum	2

Summary Statistics (House)

Mean	5.1944444
Std Dev	1.2060749
Std Err Mean	0.1421373
Upper 95% Mean	5.4778581
Lower 95% Mean	4.9110307
N	72

Quantiles (Office)

100.0%	maximum	7
99.5%		7
97.5%		7
90.0%		7
75.0%	quartile	6
50.0%	median	6
25.0%	quartile	5
10.0%		4
2.5%		2
0.5%		2
0.0%	minimum	2

Summary Statistics (Office)

Mean	5.4861111
Std Dev	1.2558938
Std Err Mean	0.1480085
Upper 95% Mean	5.7812317
Lower 95% Mean	5.1909905
N	72

The medians of Q1 for House and Office were 5 and 6, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for H and O were 4817.00 and 5623.00, and the score mean were 66.90 and 78.10. The comparison result showed that the null hypothesis cannot be rejected, hence there was no significant difference between these two groups (S=5623, Z=1.67, $p > 0.05$) (Table B.31 & Table B.32).

Table B.32 Wilcoxon Non-Parametric Rank-Sum Test for Q1 Between House and Office Samples

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
HOUSE	72	4817.00	5220.00	66.9028	-1.672
OFFICE	72	5623.00	5220.00	78.0972	1.672

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
5623	1.67187	0.0945

Easy to Manipulate – Difficult to Manipulate

Outcomes of the two seven-point Likert Scale questionnaire answers regarding the question – How easily can you manipulate the study model? - were compared using the Wilcoxon two-sample Rank-Sum test. There were n=72 entries in each test group to be compared, the total number of entries was n=144.

Table B.33 Quantiles and Summary Statistics of Participants' Response of Q2. Left: House; Right: Office

Quantiles (House)

100.0%	maximum	7
99.5%		7
97.5%		6.175
90.0%		5.7
75.0%	quartile	4.75
50.0%	median	2
25.0%	quartile	1
10.0%		1
2.5%		1
0.5%		1
0.0%	minimum	1

Summary Statistics (House)

Mean	2.8888889
Std Dev	1.7243538
Std Err Mean	0.203217
Upper 95% Mean	3.2940922
Lower 95% Mean	2.4836856
N	72

Quantiles (Office)

100.0%	maximum	7
99.5%		7
97.5%		6.175
90.0%		6
75.0%	quartile	5
50.0%	median	2
25.0%	quartile	1
10.0%		1
2.5%		1
0.5%		1
0.0%	minimum	1

Summary Statistics (Office)

Mean	3.0277778
Std Dev	1.9207703
Std Err Mean	0.2263649
Upper 95% Mean	3.4791367
Lower 95% Mean	2.5764189
N	72

The medians of Q2 for House and Office were both 2. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for H and O were 5173.00 and 5267.00, and the score mean were 71.85 and 73.15. The comparison result showed that the null hypothesis cannot be rejected, hence there was no significant difference between these two groups (S=5267, Z=0.19, p > 0.05) (Table B.33 & Table B.34).

Table B.34 Wilcoxon Non-Parametric Rank-Sum Test for Q2 Between House and Office Samples

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
HOUSE	72	5173.00	5220.00	71.8472	-0.190
OFFICE	72	5267.00	5220.00	73.1528	0.190

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
5267	0.19005	0.8493

Overall Difficulty: Easy – Difficult

Outcomes of the two seven-point Likert Scale questionnaire answers regarding the question – How easy do you think the gaming task is? - were compared using the Wilcoxon two-sample Rank-Sum test. There were n=72 entries in each test group to be compared, the total number of entries was n=144.

Table B.35 Quantiles and Summary Statistics of Participants' Response of Q3. Left: House; Right: Office

Quantiles (Left: House)

100.0%	maximum	7
99.5%		7
97.5%		7
90.0%		6
75.0%	quartile	6
50.0%	median	5
25.0%	quartile	3.25
10.0%		3
2.5%		1
0.5%		1
0.0%	minimum	1

Summary Statistics (Left: House)

Mean	4.4722222
Std Dev	1.4039404
Std Err Mean	0.165456
Upper 95% Mean	4.802132
Lower 95% Mean	4.1423124
N	72

Quantiles (Right: Office)

100.0%	maximum	7
99.5%		7
97.5%		6.175
90.0%		6
75.0%	quartile	5
50.0%	median	4
25.0%	quartile	3
10.0%		2
2.5%		1
0.5%		1
0.0%	minimum	1

Summary Statistics (Right: Office)

Mean	3.9444444
Std Dev	1.4524277
Std Err Mean	0.1711702
Upper 95% Mean	4.2857482
Lower 95% Mean	3.6031407
N	72

The medians of Q3 for House and Office were 5 and 4, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for H and O were 5746.50 and 4693.50, and the score mean were 79.81 and 65.19. The comparison result showed that the null hypothesis can be rejected, hence there was a significant difference between these two groups (S=4693.5, Z=-2.15, $p < 0.05$) (Table B.35 & Table B.36).

Table B.36 Wilcoxon Non-Parametric Rank-Sum Test for Q3 Between House and Office Samples

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
HOUSE	72	5746.50	5220.00	79.8125	2.146
OFFICE	72	4693.50	5220.00	65.1875	-2.146

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
4693.5	-2.14631	0.0318*

Gaming Task Results

1. Digital Houses versus Physical Houses

General Location

The General Location (GL) criterion was used to compare the gaming task results between Digital House and Physical House reconstructions. There were n=36 entries in each test group to be compared, the total number of entries was n=72.

Table B.37 Quantiles and Summary Statistics of Participants' Results Based on GL Criteria. Left: Digital House; Right: Physical House

Quantiles		Digital House	Physical House
100.0%	maximum	1	1
99.5%		1	1
97.5%		1	1
90.0%		1	1
75.0%	quartile	1	1
50.0%	median	0.7	1
25.0%	quartile	0.5	0.725
10.0%		0.4	0.6
2.5%		0.3	0.2
0.5%		0.3	0.2
0.0%	minimum	0.3	0.2

Summary Statistics	Digital House	Physical House
Mean	0.7055556	0.875
Std Dev	0.2460481	0.1887932
Std Err Mean	0.041008	0.0314655
Upper 95% Mean	0.7888063	0.9388784
Lower 95% Mean	0.6223048	0.8111216
N	36	36

The medians of GL for Digital House and Physical House were 0.7 and 1, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for DH and PH were 1049.00 and 1579.00, and the score mean were 29.14 and 43.86. The comparison result showed that the null hypothesis can be rejected, hence there was a significant difference between these two groups ($S=1579$, $Z=3.11$, $p < 0.05$) (Table B.37 & Table B.38).

Table B.38 Wilcoxon Non-Parametric Rank-Sum Test for GL Between Digital House and Physical House Samples

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
DH	36	1049.00	1314.00	29.1389	-3.113
PH	36	1579.00	1314.00	43.8611	3.113

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
1579	3.11251	0.0019*

Adjacency

The Adjacency (AD) criterion was used to compare the gaming task results between Digital House and Physical House reconstructions. There were n=36 entries in each test group to be compared, the total number of entries was n=72.

Table B.39 Quantiles and Summary Statistics of Participants' Results Based on AD Criteria. Left: Digital House; Right: Physical House

Digital House — Quantiles

100.0%	maximum	1
99.5%		1
97.5%		1
90.0%		0.86
75.0%	quartile	0.35
50.0%	median	0.11
25.0%	quartile	0
10.0%		0
2.5%		0
0.5%		0
0.0%	minimum	0

Digital House — Summary Statistics

Mean	0.2347222
Std Dev	0.3059084
Std Err Mean	0.0509847
Upper 95% Mean	0.3382267
Lower 95% Mean	0.1312177
N	36

Physical House — Quantiles

100.0%	maximum	1
99.5%		1
97.5%		1
90.0%		1
75.0%	quartile	1
50.0%	median	0.38
25.0%	quartile	0.085
10.0%		0.05
2.5%		0
0.5%		0
0.0%	minimum	0

Physical House — Summary Statistics

Mean	0.4747222
Std Dev	0.3966826
Std Err Mean	0.0661138
Upper 95% Mean	0.6089403
Lower 95% Mean	0.3405041
N	36

The medians of AD for Digital House and Physical House were 0.11 and 0.38, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for DH and PH were 1048.00 and 1580.00, and the score mean were 29.11 and 43.89. The comparison result showed that the null hypothesis can be rejected, hence there was a significant difference between these two groups ($S=1580$, $Z=3.01$, $p < 0.05$) (Table B.39 & Table B.40).

Table B.40 Wilcoxon Non-Parametric Rank-Sum Test for AD Between Digital House and Physical House Samples

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
DH	36	1048.00	1314.00	29.1111	-3.011
PH	36	1580.00	1314.00	43.8889	3.011

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
1580	3.01120	0.0026*

Exact Location

The Exact Location (EL) criterion was used to compare the gaming task results between Digital House and Physical House reconstructions. There were n=36 entries in each test group to be compared, the total number of entries was n=72.

Table B.41 Quantiles and Summary Statistics of Participants' Results Based on EL Criteria. Left: Digital House; Right: Physical House

Quantiles

Quantile		Digital House	Physical House
100.0%	maximum	1	1
99.5%		1	1
97.5%		1	1
90.0%		0.73	0.9
75.0%	quartile	0.5	0.8
50.0%	median	0.3	0.55
25.0%	quartile	0.125	0.2
10.0%		0	0.1
2.5%		0	0
0.5%		0	0
0.0%	minimum	0	0

Summary Statistics

Statistic	Digital House	Physical House
Mean	0.35	0.5222222
Std Dev	0.274122	0.3199206
Std Err Mean	0.045687	0.0533201
Upper 95% Mean	0.4427495	0.6304678
Lower 95% Mean	0.2572505	0.4139767
N	36	36

The medians of EL for Digital House and Physical House were 0.3 and 0.55, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for DH and PH were 1116.00 and 1512.00, and the score mean were 31.00 and 42.00. The comparison result showed that the null hypothesis can be rejected, hence there was a significant difference between these two groups (S=1512, Z=2.24, $p < 0.05$) (Table B.41 & Table B.42).

Table B.42 Wilcoxon Non-Parametric Rank-Sum Test for EL Between Digital House and Physical House Samples

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
DH	36	1116.00	1314.00	31.0000	-2.239
PH	36	1512.00	1314.00	42.0000	2.239

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
1512	2.23915	0.0251*

2. Digital Offices versus Physical Offices

General Location

The General Location (GL) criterion was used to compare the gaming task results between Digital Office and Physical Office reconstructions. There were n=36 entries in each test group to be compared, the total number of entries was n=72.

Table B.43 Quantiles and Summary Statistics of Participants' Results Based on GL Criteria. Left: Digital Office; Right: Physical Office

Quantiles

		Digital Office	Physical Office
100.0%	maximum	1	1
99.5%		1	1
97.5%		1	1
90.0%		1	1
75.0%	quartile	1	1
50.0%	median	0.6	1
25.0%	quartile	0.325	0.6
10.0%		0.1	0.4
2.5%		0	0.2
0.5%		0	0.2
0.0%	minimum	0	0.2

Summary Statistics

	Digital Office	Physical Office
Mean	0.6527778	0.7916667
Std Dev	0.3418321	0.2556504
Std Err Mean	0.056972	0.0426084
Upper 95% Mean	0.7684371	0.8781663
Lower 95% Mean	0.5371184	0.705167
N	36	36

The medians of GL for Digital Office and Physical Office were 0.6 and 1, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for DO and PO were 1167.50 and 1460.50, and the score mean were 32.43 and 40.57. The comparison result showed that the null hypothesis cannot be rejected, hence there was no significant difference between these two groups ($S=1460.5$, $Z=1.73$, $p > 0.05$) (Table B.43 & Table B.44).

Table B.44 Wilcoxon Non-Parametric Rank-Sum Test for GL Between Digital Office and Physical Office Samples

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
DO	36	1167.50	1314.00	32.4306	-1.735
PO	36	1460.50	1314.00	40.5694	1.735

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
1460.5	1.73452	0.0828

Adjacency

The Adjacency (AD) criterion was used to compare the gaming task results between Digital Office and Physical Office reconstructions. There were n=36 entries in each test group to be compared, the total number of entries was n=72.

Table B.45 Quantiles and Summary Statistics of Participants' Results Based on AD Criteria. Left: Digital Office; Right: Physical Office

Quantiles (Left: Digital Office)

100.0%	maximum	1
99.5%		1
97.5%		1
90.0%		0.916
75.0%	quartile	0.675
50.0%	median	0.25
25.0%	quartile	0.0325
10.0%		0
2.5%		0
0.5%		0
0.0%	minimum	0

Summary Statistics (Left: Digital Office)

Mean	0.3511111
Std Dev	0.3358892
Std Err Mean	0.0559815
Upper 95% Mean	0.4647597
Lower 95% Mean	0.2374625
N	36

Quantiles (Right: Physical Office)

100.0%	maximum	1
99.5%		1
97.5%		1
90.0%		1
75.0%	quartile	0.86
50.0%	median	0.53
25.0%	quartile	0.1675
10.0%		0
2.5%		0
0.5%		0
0.0%	minimum	0

Summary Statistics (Right: Physical Office)

Mean	0.5236111
Std Dev	0.3608415
Std Err Mean	0.0601402
Upper 95% Mean	0.6457023
Lower 95% Mean	0.4015199
N	36

The medians of AD for Digital Office and Physical Office were 0.25 and 0.53, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for DO and PO were 1138.00 and 1490.00, and the score mean were 31.61 and 41.39. The comparison result showed that the null hypothesis can be rejected, hence there was a significant difference between these two groups (S=1490, Z=1.99, $p < 0.05$) (Table B.45 & Table B.46).

Table B.46 Wilcoxon Non-Parametric Rank-Sum Test for AD Between Digital Office and Physical Office Samples

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
DO	36	1138.00	1314.00	31.6111	-1.990
PO	36	1490.00	1314.00	41.3889	1.990

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
1490	1.98982	0.0466*

Exact Location

The Exact Location (EL) criterion was used to compare the gaming task results between Digital Office and Physical Office reconstructions. There were n=36 entries in each test group to be compared, the total number of entries was n=72.

Table B.47 Quantiles and Summary Statistics of Participants' Results Based on EL Criteria. Left: Digital Office; Right: Physical Office

Quantiles		Digital Office	Physical Office
100.0%	maximum	1	1
99.5%		1	1
97.5%		1	1
90.0%		0.9	0.9
75.0%	quartile	0.5	0.8
50.0%	median	0.25	0.45
25.0%	quartile	0.025	0.125
10.0%		0	0
2.5%		0	0
0.5%		0	0
0.0%	minimum	0	0

Summary Statistics	Digital Office	Physical Office
Mean	0.325	0.4638889
Std Dev	0.3092618	0.3270236
Std Err Mean	0.0515436	0.0545039
Upper 95% Mean	0.4296391	0.5745378
Lower 95% Mean	0.2203609	0.35324
N	36	36

The medians of EL for Digital Office and Physical Office were 0.25 and 0.45, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for DO and PO were 1152.00 and 1476.00, and the score mean were 32.00 and 41.00. The comparison result showed that the null hypothesis cannot be rejected, hence there was no significant difference between these two groups ($S=1476$, $Z=1.83$, $p > 0.05$) (Table B.47 & Table B.48).

Table B.48 Wilcoxon Non-Parametric Rank-Sum Test for EL Between Digital Office and Physical Office Samples

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
DO	36	1152.00	1314.00	32.0000	-1.832
PO	36	1476.00	1314.00	41.0000	1.832

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
1476	1.83236	0.0669

3. Digital Houses versus Digital Offices

General Location

The General Location (GL) criterion was used to compare the gaming task results between Digital House and Digital Office reconstructions. There were n=36 entries in each test group to be compared, the total number of entries was n=72.

Table B.49 Quantiles and Summary Statistics of Participants' Results Based on GL Criteria. Left: Digital House; Right: Digital Office

Quantiles		Digital House	Digital Office
100.0%	maximum	1	1
99.5%		1	1
97.5%		1	1
90.0%		1	1
75.0%	quartile	1	1
50.0%	median	0.7	0.6
25.0%	quartile	0.5	0.325
10.0%		0.4	0.1
2.5%		0.3	0
0.5%		0.3	0
0.0%	minimum	0.3	0

Summary Statistics	Digital House	Digital Office
Mean	0.7055556	0.6527778
Std Dev	0.2460481	0.3418321
Std Err Mean	0.041008	0.056972
Upper 95% Mean	0.7888063	0.7684371
Lower 95% Mean	0.6223048	0.5371184
N	36	36

The medians of GL for Digital House and Digital Office were 0.7 and 0.6, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for DH and DO were 1343.00 and 1285.00, and the score mean were 37.31 and 35.69. The comparison result showed that the null hypothesis cannot be rejected, hence there was no significant difference between these two groups (S=1285, Z=-0.33, $p > 0.05$) (Table B.49 & Table B.50).

Table B.50 Wilcoxon Non-Parametric Rank-Sum Test for GL Between Digital House and Digital Office Samples

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
DH	36	1343.00	1314.00	37.3056	0.328
DO	36	1285.00	1314.00	35.6944	-0.328

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
1285	-0.32825	0.7427

Adjacency

The Adjacency (AD) criterion was used to compare the gaming task results between Digital House and Digital Office reconstructions. There were n=36 entries in each test group to be compared, the total number of entries was n=72.

Table B.51 Quantiles and Summary Statistics of Participants' Results Based on AD Criteria. Left: Digital House; Right: Digital Office

Quantiles

Quantile		Digital House	Digital Office
100.0%	maximum	1	1
99.5%		1	1
97.5%		1	1
90.0%		0.86	0.916
75.0%	quartile	0.35	0.675
50.0%	median	0.11	0.25
25.0%	quartile	0	0.0325
10.0%		0	0
2.5%		0	0
0.5%		0	0
0.0%	minimum	0	0

Summary Statistics

Statistic	Digital House	Digital Office
Mean	0.2347222	0.3511111
Std Dev	0.3059084	0.3358892
Std Err Mean	0.0509847	0.0559815
Upper 95% Mean	0.3382267	0.4647597
Lower 95% Mean	0.1312177	0.2374625
N	36	36

The medians of AD for Digital House and Digital Office were 0.11 and 0.25, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for DH and DO were 1180.50 and 1447.50, and the score mean were 32.79 and 40.21. The comparison result showed that the null hypothesis cannot be rejected, hence there was no significant difference between these two groups (S=1447.5, Z=1.52, $p > 0.05$) (Table B.51 & Table B.52).

Table B.52 Wilcoxon Non-Parametric Rank-Sum Test for AD Between Digital House and Digital Office Samples

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
DH	36	1180.50	1314.00	32.7917	-1.518
DO	36	1447.50	1314.00	40.2083	1.518

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
1447.5	1.51767	0.1291

Exact Location

The Exact Location (EL) criterion was used to compare the gaming task results between Digital House and Digital Office reconstructions. There were n=36 entries in each test group to be compared, the total number of entries was n=72.

Table B.53 Quantiles and Summary Statistics of Participants' Results Based on EL Criteria. Left: Digital House; Right: Digital Office

Digital House

Quantiles		
100.0%	maximum	1
99.5%		1
97.5%		1
90.0%		0.73
75.0%	quartile	0.5
50.0%	median	0.3
25.0%	quartile	0.125
10.0%		0
2.5%		0
0.5%		0
0.0%	minimum	0

Summary Statistics	
Mean	0.35
Std Dev	0.274122
Std Err Mean	0.045687
Upper 95% Mean	0.4427495
Lower 95% Mean	0.2572505
N	36

Digital Office

Quantiles		
100.0%	maximum	1
99.5%		1
97.5%		1
90.0%		0.9
75.0%	quartile	0.5
50.0%	median	0.25
25.0%	quartile	0.025
10.0%		0
2.5%		0
0.5%		0
0.0%	minimum	0

Summary Statistics	
Mean	0.325
Std Dev	0.3092618
Std Err Mean	0.0515436
Upper 95% Mean	0.4296391
Lower 95% Mean	0.2203609
N	36

The medians of EL for Digital House and Digital Office were 0.3 and 0.25, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for DH and DO were 1374.00 and 1254.00, and the score mean were 38.17 and 34.83. The comparison result showed that the null hypothesis cannot be rejected, hence there was no significant difference between these two groups (S=1254, Z=-0.68, $p > 0.05$) (Table B.53 & Table B.54).

Table B.54 Wilcoxon Non-Parametric Rank-Sum Test for EL Between Digital House and Digital Office Samples

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
DH	36	1374.00	1314.00	38.1667	0.676
DO	36	1254.00	1314.00	34.8333	-0.676

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
1254	-0.67579	0.4992

4. Physical Houses versus Physical Offices

General Location

The General Location (GL) criterion was used to compare the gaming task results between Physical House and Physical Office reconstructions. There were n=36 entries in each test group to be compared, the total number of entries was n=72.

Table B.55 Quantiles and Summary Statistics of Participants' Results Based on GL Criteria. Left: Physical House; Right: Physical Office

Quantiles		Physical House	Physical Office
100.0%	maximum	1	1
99.5%		1	1
97.5%		1	1
90.0%		1	1
75.0%	quartile	1	1
50.0%	median	1	1
25.0%	quartile	0.725	0.6
10.0%		0.6	0.4
2.5%		0.2	0.2
0.5%		0.2	0.2
0.0%	minimum	0.2	0.2

Summary Statistics	Physical House	Physical Office
Mean	0.875	0.7916667
Std Dev	0.1887932	0.2556504
Std Err Mean	0.0314655	0.0426084
Upper 95% Mean	0.9388784	0.8781663
Lower 95% Mean	0.8111216	0.705167
N	36	36

The medians of GL for Physical House and Physical Office were 0.725 and 0.6, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for PH and PO were 1407.50 and 1220.50, and the score mean were 39.10 and 33.90. The comparison result showed that the null hypothesis cannot be rejected, hence there was no significant difference between these two groups (S=1220.5, Z=-1.15, p > 0.05) (Table B.55 & Table B.56).

Table B.56 Wilcoxon Non-Parametric Rank-Sum Test for GL Between Physical House and Physical Office Samples

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
PH	36	1407.50	1314.00	39.0972	1.153
PO	36	1220.50	1314.00	33.9028	-1.153

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
1220.5	-1.15253	0.2491

Adjacency

The Adjacency (AD) criterion was used to compare the gaming task results between Physical House and Physical Office reconstructions. There were n=36 entries in each test group to be compared, the total number of entries was n=72.

Table B.57 Quantiles and Summary Statistics of Participants' Results Based on AD Criteria. Left: Physical House; Right: Physical Office

Quantiles

		Physical House	Physical Office
100.0%	maximum	1	1
99.5%		1	1
97.5%		1	1
90.0%		1	1
75.0%	quartile	1	0.86
50.0%	median	0.38	0.53
25.0%	quartile	0.085	0.1675
10.0%		0.05	0
2.5%		0	0
0.5%		0	0
0.0%	minimum	0	0

Summary Statistics

	Physical House	Physical Office
Mean	0.4747222	0.5236111
Std Dev	0.3966826	0.3608415
Std Err Mean	0.0661138	0.0601402
Upper 95% Mean	0.6089403	0.6457023
Lower 95% Mean	0.3405041	0.4015199
N	36	36

The medians of AD for Physical House and Physical Office were 0.38 and 0.53, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for PH and PO were 1291.00 and 1337.00, and the score mean were 35.86 and 37.14. The comparison result showed that the null hypothesis cannot be rejected, hence there was no significant difference between these two groups (S=1337, Z=0.25, $p > 0.05$) (Table B.57 & Table B.58).

Table B.58 Wilcoxon Non-Parametric Rank-Sum Test for AD Between Physical House and Physical Office Samples

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
PH	36	1291.00	1314.00	35.8611	-0.255
PO	36	1337.00	1314.00	37.1389	0.255

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
1337	0.25469	0.7990

Exact Location

The Exact Location (EL) criterion was used to compare the gaming task results between Physical House and Physical Office reconstructions. There were n=36 entries in each test group to be compared, the total number of entries was n=72.

Table B.59 Quantiles and Summary Statistics of Participants' Results Based on EL Criteria. Left: Physical House; Right: Physical Office

Quantiles (Physical House)

100.0%	maximum	1
99.5%		1
97.5%		1
90.0%		0.9
75.0%	quartile	0.8
50.0%	median	0.55
25.0%	quartile	0.2
10.0%		0.1
2.5%		0
0.5%		0
0.0%	minimum	0

Summary Statistics (Physical House)

Mean	0.5222222
Std Dev	0.3199206
Std Err Mean	0.0533201
Upper 95% Mean	0.6304678
Lower 95% Mean	0.4139767
N	36

Quantiles (Physical Office)

100.0%	maximum	1
99.5%		1
97.5%		1
90.0%		0.9
75.0%	quartile	0.8
50.0%	median	0.45
25.0%	quartile	0.125
10.0%		0
2.5%		0
0.5%		0
0.0%	minimum	0

Summary Statistics (Physical Office)

Mean	0.4638889
Std Dev	0.3270236
Std Err Mean	0.0545039
Upper 95% Mean	0.5745378
Lower 95% Mean	0.35324
N	36

The medians of EL for Physical House and Physical Office were 0.55 and 0.45, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for PH and PO were 1388.00 and 1240.00, and the score mean were 38.56 and 34.44. The comparison result showed that the null hypothesis cannot be rejected, hence there was no significant difference between these two groups (S=1240, Z=-0.83, p > 0.05) (Table B.59 & Table B.60).

Table B.60 Wilcoxon Non-Parametric Rank-Sum Test for EL Between Physical House and Physical Office Samples

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
PH	36	1388.00	1314.00	38.5556	0.833
PO	36	1240.00	1314.00	34.4444	-0.833

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
1240	-0.83314	0.4048

5. Digital versus Physical

General Location

The General Location (GL) criterion was used to compare the gaming task results between the overall Digital and Physical. There were n=72 entries in each test group to be compared, the total number of entries was n=144.

Table B.61 Quantiles and Summary Statistics of Participants' Results Based on GL Criteria. Left: Digital; Right: Physical

Quantiles

		Digital	Physical
100.0%	maximum	1	1
99.5%		1	1
97.5%		1	1
90.0%		1	1
75.0%	quartile	1	1
50.0%	median	0.7	1
25.0%	quartile	0.4	0.7
10.0%		0.3	0.43
2.5%		0	0.2
0.5%		0	0.2
0.0%	minimum	0	0.2

Summary Statistics

	Digital	Physical
Mean	0.6791667	0.8333333
Std Dev	0.296903	0.2270447
Std Err Mean	0.0349904	0.0267575
Upper 95% Mean	0.7489355	0.8866862
Lower 95% Mean	0.6093979	0.7799804
N	72	72

The medians of GL for Digital and Physical were 0.7 and 1, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for D and P were 4434.50 and 6005.50, and the score mean were 61.59 and 83.41. The comparison result showed that the null hypothesis can be rejected, hence there was a significant difference between these two groups ($S=6005.5$, $Z=3.29$, $p < 0.05$) (Table B.61 & Table B.62).

Table B.62 Wilcoxon Non-Parametric Rank-Sum Test for GL Between Digital and Physical

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
DIGITAL	72	4434.50	5220.00	61.5903	-3.291
PHYSICAL	72	6005.50	5220.00	83.4097	3.291

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
6005.5	3.29059	0.0010*

Adjacency

The Adjacency (AD) criterion was used to compare the gaming task results between the overall Digital and Physical. There were n=72 entries in each test group to be compared, the total number of entries was n=144.

Table B.63 Quantiles and Summary Statistics of Participants' Results Based on AD Criteria. Left: Digital; Right: Physical

Quantiles (Digital)

100.0%	maximum	1
99.5%		1
97.5%		1
90.0%		0.874
75.0%	quartile	0.45
50.0%	median	0.15
25.0%	quartile	0
10.0%		0
2.5%		0
0.5%		0
0.0%	minimum	0

Summary Statistics (Digital)

Mean	0.2929167
Std Dev	0.324317
Std Err Mean	0.0382211
Upper 95% Mean	0.3691274
Lower 95% Mean	0.2167059
N	72

Quantiles (Physical)

100.0%	maximum	1
99.5%		1
97.5%		1
90.0%		1
75.0%	quartile	0.86
50.0%	median	0.4
25.0%	quartile	0.13
10.0%		0.012
2.5%		0
0.5%		0
0.0%	minimum	0

Summary Statistics (Physical)

Mean	0.4991667
Std Dev	0.3773098
Std Err Mean	0.0444664
Upper 95% Mean	0.5878301
Lower 95% Mean	0.4105032
N	72

The medians of AD for Digital and Physical were 0.15 and 0.4, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for D and P were 4368.50 and 6071.50, and the score mean were 60.67 and 84.33. The comparison result showed that the null hypothesis can be rejected, hence there was a significant difference between these two groups ($S=6071.5$, $Z=3.42$, $p < 0.05$) (Table B.63 & Table B.64).

Table B.64 Wilcoxon Non-Parametric Rank-Sum Test for AD Between Digital and Physical

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
DIGITAL	72	4368.50	5220.00	60.6736	-3.419
PHYSICAL	72	6071.50	5220.00	84.3264	3.419

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
6071.5	3.41857	0.0006*

Exact Location

The Exact Location (EL) criterion was used to compare the gaming task results between the overall Digital and Physical. There were n=72 entries in each test group to be compared, the total number of entries was n=144.

Table B.65 Quantiles and Summary Statistics of Participants' Results Based on EL Criteria. Left: Digital; Right: Physical

Digital

Quantiles		
100.0%	maximum	1
99.5%		1
97.5%		1
90.0%		0.8
75.0%	quartile	0.5
50.0%	median	0.3
25.0%	quartile	0.1
10.0%		0
2.5%		0
0.5%		0
0.0%	minimum	0

Summary Statistics	
Mean	0.3375
Std Dev	0.2904283
Std Err Mean	0.0342273
Upper 95% Mean	0.4057473
Lower 95% Mean	0.2692527
N	72

Physical

Quantiles		
100.0%	maximum	1
99.5%		1
97.5%		1
90.0%		0.9
75.0%	quartile	0.8
50.0%	median	0.5
25.0%	quartile	0.2
10.0%		0.1
2.5%		0
0.5%		0
0.0%	minimum	0

Summary Statistics	
Mean	0.4930556
Std Dev	0.3225455
Std Err Mean	0.0380124
Upper 95% Mean	0.56885
Lower 95% Mean	0.4172611
N	72

The medians of EL for Digital and Physical were 0.3 and 0.5, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for D and P were 4502.50 and 5937.50, and the score mean were 62.53 and 82.47. The comparison result showed that the null hypothesis can be rejected, hence there was a significant difference between these two groups ($S=5937.5$, $Z=2.88$, $p < 0.05$) (Table B.65 & Table B.66).

Table B.66 Wilcoxon Non-Parametric Rank-Sum Test for EL Between Digital and Physical

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
DIGITAL	72	4502.50	5220.00	62.5347	-2.881
PHYSICAL	72	5937.50	5220.00	82.4653	2.881

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
5937.5	2.88123	0.0040*

6. Houses versus Offices

General Location

The General Location (GL) criterion was used to compare the gaming task results between the overall House and Office. There were n=72 entries in each test group to be compared, the total number of entries was n=144.

Table B.67 Quantiles and Summary Statistics of Participants' Results Based on GL Criteria. Left: House; Right: Office

Quantiles

		House	Office
100.0%	maximum	1	1
99.5%		1	1
97.5%		1	1
90.0%		1	1
75.0%	quartile	1	1
50.0%	median	0.9	0.8
25.0%	quartile	0.6	0.5
10.0%		0.4	0.3
2.5%		0.2825	0
0.5%		0.2	0
0.0%	minimum	0.2	0

Summary Statistics

	House	Office
Mean	0.7902778	0.7222222
Std Dev	0.2338651	0.3077507
Std Err Mean	0.0275613	0.0362688
Upper 95% Mean	0.8452334	0.7945401
Lower 95% Mean	0.7353222	0.6499044
N	72	72

The medians of GL for House and Office were 0.9 and 0.8, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for H and O were 5429.50 and 5010.50, and the score mean were 75.41 and 69.59. The comparison result showed that the null hypothesis cannot be rejected, hence there was no significant difference between these two groups (S=5010.5, Z=-0.88, p > 0.05) (Table B.67 & Table B.68).

Table B.68 Wilcoxon Non-Parametric Rank-Sum Test for GL Between House and Office

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
HOUSE	72	5429.50	5220.00	75.4097	0.876
OFFICE	72	5010.50	5220.00	69.5903	-0.876

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
5010.5	-0.87609	0.3810

Adjacency

The Adjacency (AD) criterion was used to compare the gaming task results between the overall House and Office. There were n=72 entries in each test group to be compared, the total number of entries was n=144.

Table B.69 Quantiles and Summary Statistics of Participants' Results Based on AD Criteria. Left: House; Right: Office

Quantiles (House)

100.0%	maximum	1
99.5%		1
97.5%		1
90.0%		1
75.0%	quartile	0.65
50.0%	median	0.2
25.0%	quartile	0.05
10.0%		0
2.5%		0
0.5%		0
0.0%	minimum	0

Summary Statistics (House)

Mean	0.3547222
Std Dev	0.3718927
Std Err Mean	0.043828
Upper 95% Mean	0.4421127
Lower 95% Mean	0.2673317
N	72

Quantiles (Office)

100.0%	maximum	1
99.5%		1
97.5%		1
90.0%		0.964
75.0%	quartile	0.8325
50.0%	median	0.38
25.0%	quartile	0.13
10.0%		0
2.5%		0
0.5%		0
0.0%	minimum	0

Summary Statistics (Office)

Mean	0.4373611
Std Dev	0.3568564
Std Err Mean	0.0420559
Upper 95% Mean	0.5212182
Lower 95% Mean	0.353504
N	72

The medians of AD for House and Office were 0.2 and 0.38, respectively. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for H and O were 4909.00 and 5531.00, and the score mean were 68.18 and 76.82. The comparison result showed that the null hypothesis cannot be rejected, hence there was no significant difference between these two groups (S=5531, Z=1.25, $p > 0.05$) (Table B.69 & Table B.70).

Table B.70 Wilcoxon Non-Parametric Rank-Sum Test for AD Between House and Office

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
HOUSE	72	4909.00	5220.00	68.1806	-1.247
OFFICE	72	5531.00	5220.00	76.8194	1.247

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
5531	1.24732	0.2123

Exact Location

The Exact Location (EL) criterion was used to compare the gaming task results between the overall House and Office. There were n=72 entries in each test group to be compared, the total number of entries was n=144.

Table B.71 Quantiles and Summary Statistics of Participants' Results Based on EL Criteria. Left: House; Right: Office

Quantiles			Quantiles		
100.0%	maximum	1	100.0%	maximum	1
99.5%		1	99.5%		1
97.5%		1	97.5%		1
90.0%		0.9	90.0%		0.9
75.0%	quartile	0.7	75.0%	quartile	0.675
50.0%	median	0.4	50.0%	median	0.4
25.0%	quartile	0.2	25.0%	quartile	0.1
10.0%		0.1	10.0%		0
2.5%		0	2.5%		0
0.5%		0	0.5%		0
0.0%	minimum	0	0.0%	minimum	0

Summary Statistics		Summary Statistics	
Mean	0.4361111	Mean	0.3944444
Std Dev	0.3082461	Std Dev	0.3236625
Std Err Mean	0.0363271	Std Err Mean	0.038144
Upper 95% Mean	0.5085454	Upper 95% Mean	0.4705014
Lower 95% Mean	0.3636768	Lower 95% Mean	0.3183875
N	72	N	72

The medians of EL for House and Office were both 0.4. A Non-Parametric confidence interval of 0.95 was used in this test. The score sum for H and O were 5463.50 and 4976.50, and the score mean were 75.88 and 69.12. The comparison result showed that the null hypothesis cannot be rejected, hence there was no significant difference between these two groups (S=4976.5, Z=-0.98, $p > 0.05$) (Table B.71 & Table B.72).

Table B.72 Wilcoxon Non-Parametric Rank-Sum Test for EL Between House and Office

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
HOUSE	72	5463.50	5220.00	75.8819	0.976
OFFICE	72	4976.50	5220.00	69.1181	-0.976

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
4976.5	-0.97648	0.3288

APPENDIX C: INFORMED CONSENT FOR GAMING TASKS

Student Researcher(s): Yin Jiang

Title of Project: *Between 3-D Computer Models and 3-D Printed Models: People's Understanding and Preference (PART I: GAMING EXPERIMENT)*

I am asking for your voluntary participation in my doctoral research project. Please read the following information about the project. If you would like to participate, please sign in the appropriate box below.

Purpose of the project: To investigate people's understanding of geometric layout.

If you participate, you will be asked to: Look at two types of architectural models and reassemble the building or building complex based on your memory. And then you will be asked to answer a few questions regarding your experience.

Time required for participation: 20-25 minutes

Reward: 3 out of 100 extra course credits

How confidentiality will be maintained: Information about you will be kept confidential to the extent permitted or required by law. People who have access to your information include the Principal Investigator and research study personnel. Representatives of regulatory agencies such as the Office of Human Research Protections (OHRP) and entities such as the Texas A&M University Human Subjects Protection Program may access your records to make sure the study is being run correctly and that information is collected properly.

Voluntary Participation:

Participation in this study is completely voluntary. If you decide not to participate there will not be any negative consequences. Please be aware that if you decide to participate, you may stop participating at any time and you may decide not to answer any specific question.

Contact Information:

- **The researcher: Yin Jiang. E-mail: jiangyin@tamu.edu. Phone: 979-422-2182**
- **For questions about your rights as a research participant; or if you have questions, complaints, or concerns about the research, you may call the Texas A&M University Human Subjects Protection Program office at (979) 458-4067 or irb@tamu.edu.**

By signing this form I am attesting that I have read and understand the information above and I freely give my consent/assent to participate or permission for my child to participate.

Adult Informed Consent

Date Reviewed & Signed: ______________________________

Signature: ______________________________

Printed Name of Research Participant: ____________________________

Signature: ____________________________

APPENDIX D: INFORMED CONSENT FOR INTERVIEWS

Student Researcher(s): Yin Jiang

Title of Project: *Between 3-D Computer Models and 3-D Printed Models: People's Understanding and Preference (PART II: INTERVIEW)*

I am asking for your voluntary participation in my doctoral research project. Please read the following information about the project. If you would like to participate, please sign in the appropriate box below.

Purpose of the project: To investigate design professionals' experience and ideas towards their clients' understanding and preference regarding 3-D digital models and physical models.

If you participate, you will be asked to: Participate in a semi-structured interview with me, while I will ask you a series of pre-determined questions, and you can also express your ideas freely regarding this subject.

Time required for participation: 30-60 minutes.

How confidentiality will be maintained: I will audio record the conversation, in order to extract the information later. The recorded data will be stored safely in an encrypted drive and only accessible by myself. The data will be completely shredded after the completion of this study. You cannot participate, if you do not want this interview to be audio recorded.

Information about you will be kept confidential to the extent permitted or required by law. People who have access to your information include the Principal Investigator and research study personnel. Representatives of regulatory agencies such as the Office of Human Research Protections (OHRP) and entities such as the Texas A&M University Human Subjects Protection Program may access your records to make sure the study is being run correctly and that information is collected properly.

Voluntary Participation:

Participation in this study is completely voluntary. If you decide not to participate there will not be any negative consequences. Please be aware that if you decide to participate, you may stop participating at any time and you may decide not to answer any specific question.

Contact Information:

- **The researcher: Yin Jiang. E-mail: jiangyin@tamu.edu. Phone: 979-422-2182**
- **For questions about your rights as a research participant; or if you have questions, complaints, or concerns about the research, you may call the Texas A&M University Human Subjects Protection Program office at (979) 458-4067 or irb@tamu.edu.**

By signing this form I am attesting that I have read and understand the information above and I freely give my consent/assent to participate or permission for my child to participate.

Adult Informed Consent

Date Reviewed & Signed: ___________________________
Signature: ___________________________

Printed Name of Research Participant: __________________________
Signature: __________________________

APPENDIX E: SURVEY QUESTIONNAIRE

Survey questionnaire for gaming task

How pleasant does the study model look?

Unpleasant						Pleasant
1	2	3	4	5	6	7

How easily can you manipulate the study model?

Easy						Difficult
1	2	3	4	5	6	7

Overall, you think this gaming task is:

Easy						Difficult
1	2	3	4	5	6	7